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AN INSTANTANEOUS VELOCITY RECORDER: ITS CONSTRUCTION AND EVALUATION

BY

© RICHARD ALAN BATES

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "An Instantaneous Velocity Recorder: Its Construction and Evaluation" submitted by Richard Alan Bates in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

ABSTRACT

An instantaneous velocity recording device (Plate 1) was constructed for directly obtaining (by plotting on an XYY' recorder) the horizontal velocity of sprinters over 100 meters. A lightweight nylon cord (1.75% stretch per kilogram of load) tied around the sprinter's waist provided the driving force for a chopper (100 slots). This chopper served to break up a light source (6 volt incandescent bulb) which illuminated a photodiode (response time of less than 1 microsecond). The faster the chopper turned the more impulses that were produced. These impulses were electronically amplified, squared and averaged, using the components of a Heath Analog Digital Designer, resulting in a direct current output in porportion to the number of impulses. The changes in the direct current output (instantaneous velocity) were recorded on the Y axis of a Honeywell recorder. Instantaneous velocity corresponded to average velocity over eight to eighty centimeters (See text, Figure 7).

Since twenty-five revolutions of the chopper occurred when one meter of cord was pulled out, 2500 impulses were generated per meter (100 slots x 25 revolutions). An electronic counting circuit was designed, using the components of the Heath Analog Digital Designer, and two Motorola decade counters, to yield one impulse for every 2500 counted. This output was connected to the Y' axis of the Honeywell XYY' recorder

and thus provided an event mark for every meter of cord pulled out.

The X axis of the Honeywell XYY' recorder was set to sweep at the rate of two centimeters per second. A remote control switch at the 100 meter mark started the sweep axis on the starter's "Set" command and reset the sweep when the sprinter crossed the 100 meter mark, and thus provided times for the 100 meter sprint.

One hundred and thirty meters of cord were stored in a separate takeup reel which was also provided with a rewind motor. One hundred meters of cord could be rewound in approximately fifteen seconds. The takeup reel and chopper were provided with brakes (disengaged with tension in the cord; engaged when tension released) for controlling the motion of both wheels and matching the velocity of the applied force on the cord.

The device and its circuitry were tested electronically and also calibrated with known velocities. It was found to be very accurate (less than 3% underestimation) and reliable (95% test-retest error comparison). A number of 100 meter sprints were recorded and the device was found to be a convenient and useful tool in evaluating a sprinter's performance. It was found that little extra cord was pulled out due to sag of the cord or due to wind; there was, however, a 4.33% error in the event marker (see text, Chapter IV).

PLATE I: - INSTANTANEOUS VELOCITY RECORDER

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INTRODUCTION

Of all the sports records which man has assailed one of the least yielding has been the 100 meter sprint record. For example, the Olympic record has only been improved by four tenth's of a second in over forty years of competition; and the current world record for 100 yards is 9.1 seconds, whereas in 1890 it was 9.8 seconds. If sprinting records were subjected to a statistical analysis it is doubtful whether there would be a significant improvement given the variance of sprinting times each year.

The hypothesis naturally arises that man's maximal sprinting speed is limited and can't be changed with training. As many factors have been advanced as limits to speed as there are years that the record times have withstood competition. Among the limits to speed that have been advanced are: strength, flexibility, reaction time, speed of muscle shortening, viscosity of muscle, stride length, stride frequency, myoglobin stores, muscle energy sources such as ATP or CP, neural fatigue, and skill.

Training techniques have been just as numerous in the attempt to set new world records. More recently the techniques have included uphill running[1], downhill running[2], sprinting with weights[3], being towed behind

a car[4], or running on a high speed treadmill[5,6].

Active research in sprinting started in 1926 with A.V. Hill. Why haven't the questions been answered and the best techniques been found? Whether the answer lies with physiological, biomechanical, neurological, or psycho-motor parameters there must be a means of identifying what exactly is happening to the sprinter on the track throughout the entire 100 meters.

At present, most investigations have used improvement in 100 meter times as the basis for the evaluation of parameters studied. Although this is the ultimate concern it lends itself to few conclusions regarding the parameters examined. If a subject is run five to ten times, a range of scores will be obtained that may vary as much as one second. A training program of six weeks may produce two to five tenth's of a second improvement. Time over 100 meters is too gross a measure -- any improvement in time is masked and it is impossible to tell how the improvement in time occurred. How could a training program to improve a sprinter's top speed be conducted without an adequate measuring device? The situation could be compared to one in gymnastics -- trying to determine what factors contribute to the performance of a gymnastics routine and using the scores obtained in a series of competitions.

To conduct an investigation into some process to identify the factors involved and to decide whether or not they can be changed requires an accurate measuring device. For example, a training program designed to

increase top speed could be evaluated very accurately if a device measuring instantaneous velocity were available. A simple check of velocity recordings of sprints before and after training would indicate whether improvement in top speed had occurred.

THE PROBLEM

The purpose of this study was to obtain instantaneous velocity curves of the upper torso of a sprinter over the entire distance of 100 meters. The problem under investigation was the development of a measuring system for obtaining instantaneous sprinting velocity curves, and the evaluation of such a measuring system.

LIMITATIONS

1. Financial assistance was limited and thus necessitated the development of an electro-mechanical measuring system rather than a non-contact electronic servo system.

DELIMITATIONS

1. Using a measuring system with a mechanical link to the sprinter limited the measurement to that of horizontal velocity only.
2. The study was limited to measuring the velocity of a sprinter over a distance of 100 meters.

3. Instantaneous speed was limited to average speed over the distance of eight to eighty centimeters.

DEFINITION OF TERMS

SPRINTING VELOCITY:

Sprinting velocity was defined as the horizontal velocity of a sprinter over 100 meters. In the past researchers have referred to average sprinting speed: the distance of 100 meters divided by the time taken to cover this distance.

INSTANTANEOUS SPRINTING VELOCITY:

The distance of eight centimeters up to eighty centimeters divided by the time taken to cover this distance was referred to as the instantaneous velocity of a sprinter.

INSTANTANEOUS VELOCITY CURVE:

This curve was a graphic representation of the sprinter's instantaneous velocity over the entire distance of 100 meters.

ELECTRO-MECHANICAL SYSTEM:

A method of obtaining the instantaneous velocity of a sprinter which utilized a mechanical link to the sprinter to drive some device from which electronic measurements could be made.

<u>NON-CONTACT ELECTRONIC SERVO SYSTEM:</u>

A method of obtaining the instantaneous velocity of a sprinter in which it was not necessary for direct contact with the sprinter to drive the device from which electronic measurements could be made.

<u>PHOTODIODE:</u>

A light-sensitive device which gave rise to a small electrical current on exposure to a light impulse.

<u>CHOPPER</u>:

A wheel with slots located on the circumference which turned on an axis and served to break up in a regular manner a constant light source exposing a photodiode.

<u>RATE METER</u>:

An electronic device which converted electrical impulses to a direct voltage level in proportion to the frequency of the impulses.

CHAPTER II

CONSTRUCTION OF VELOCITY RECORDER

REVIEW OF THE LITERATURE

DIRECT MEASURES OF SPRINTING SPEED:

There are relatively very few methods of determining a sprinter's speed over 100 meters. The problem is basically technological -- how to tell how fast a sprinter is going without interfering with his sprint.

The original speed measurements were those by Hill in 1927 using a timing device which recorded the current induced in a galvanometer by a magnet carried past the timing stations by the runner. These timing stations were spaced 10 yards apart.

Karpovich[8] in 1930 used a string wound on a drum to record the speed of a swimmer. More recently, Karpovich and Karpovich[9] have built a magnetic tape natograph which automatically recorded the speed of a swimmer in feet per second. The swimmer pulled a magnetic tape with a pre-recorded signal of constant frequency through a playback head. The frequency of the signals passing through the playback head was converted to a voltage and recorded by an ink recorder. The swimmer had to pull a wooden tripod to which the tape was attached. The principle seems adequate but the techniques are difficult to apply directly to track sprinting.

Henry[10] in 1951 has used a series of timing stations spaced five yards apart to obtain average speed over five yards for a distance of fifty yards. These timing stations consisted of a bamboo stick with special hinge attached which opened and closed an electric circuit when the sprinter hit the stick. He confirmed Hill's result of 1927 that the velocity during a dash increased from zero to a maximum at fifty yards, but added that the peak occurred at six seconds if running "all out", regardless of speed. One other interesting point he made was that it was physiologically impossible once peak speed was reached to maintain it for more than fifteen to twenty yards and even the best sprinters had a velocity decrement of 3% in the last part of the 100. The first fifteen yards of the sprint could not be timed because of the rapidly changing speed and thus was estimated in all of Henry's studies.

Cinematographical analysis has been used to record the velocity of the center of gravity of a sprinter, with corrections for distortions caused by panning the camera: however, the monumental amount of time involved in the analysis has precluded its use. Several authors have studied short sections of a sprint by this method. For example, Deshon and Nelson[11] looked at the section from 25 - 40 yards and Baird[12] has filmed skaters with a light on their helmets.

More recently, photoconductive cells have been used by Jackson and Cooper[13] spaced at the 0, 20, 30, 40 and 50 yard marks. At best this gives average speed over ten yards and no real indication of what is occurring in between. Photocell densities close enough for instantaneous velocity

measurements are prohibitively expensive. Some problem also exists with the arm movements triggering the photocells.

Bates and Gutoski[14] have designed a recording device which yielded a time for every meter of a 100 meter sprint. The basic principle was event marks (generated by knots every meter in a cord pulled out by the sprinter depressing a microswitch) recorded on a time base. However, tedious calculations were involved in calculating the velocity of the sprinter.

RELATED METHODS OF MEASURING VELOCITY:

The most widely used non-contact methods for tracking objects and measuring their velocities have been based on the doppler effect. If an object, with a constant frequency sound or light source attached, moved in any direction the emitted waves would tend to pile up ahead of the direction of travel and would tend to be spaced out behind the direction of motion. The faster the object moved the more tightly piled and greater spaced these waves would become. A listener would be able to detect the change in position of the object as a direct result of a change in wave length or frequency. Often this changing frequency would be combined with another fixed frequency at the listener to give rise to beats -- the number of beats per second representing the difference of the two frequencies. For example, a radar system would send out its own light beam which would be reflected back from objects such as automobiles, and give rise to a doppler effect as the object moved. To detect the velocity of stars the wavelength of the light reaching earth has been

measured. Satellites commonly have a known frequency source which would be recorded on earth as an apparent frequency and combined with another fixed frequency on earth to give rise to beats. As the satellite passed overhead the pitch of the beats would change.

Mechanical devices have been generally applicable either to objects which moved over short distances, such as a die-set (for precision molds), or if the object moved over greater distances then it was possible to have a direct mechanical link to some part in continuous contact with the ground as the object moved, such as the wheel of an automobile. A wide variety of transducers have been developed to measure flow, force, rotation, pressure, etc. with time. Examples of transducers in common use would include strain gauge transducers, and ferromagnetic toothed rotor tachometers[15]. One type of transducer used in this study was a photoelectrical tachometer.

EXPECTED FORCES:

Looking at a sprinter of 150 pounds one could expect, depending on the experience of the sprinter, a horizontal velocity of ten to twelve feet per second and an acceleration of fifty to seventy feet per second squared just after leaving the blocks[16,17]. Based on the speed of the fastest human, Bob Hayes (26.9 mph), one could expect the sprinter to reach a speed of something less than 12.0 meters per second at the fastest point in the 100 meters

Since one could expect initially a horizontal force of approximately

300 pounds (150/32 x 64) decreasing to approximately 20 pounds (150/32 x 4). Thus the system developed for measuring velocity must have a range of speeds from zero to twenty-seven miles per hour, be capable of withstanding large starting forces and yet, at the same time, be sensitive enough to respond to changes in velocity.

CONSIDERATIONS

IDEAL SYSTEM:

In considering what would be the ideal system it is necessary to keep in mind considerations of practicality and convenience as well as accuracy. Plotting the center of gravity of the body would be the only means of obtaining the velocity, acceleration, and forces involved in propelling the body. A servo system which followed the sprinter and at the same time could be used for estimation of the center of gravity might schematically look like Figure 1.

The servo mechanism could be a bank of infra red detectors which could be attached to a television camera to monitor the center of gravity.

A light source or sound source could be carried by the sprinter and his velocity could be calculated using doppler shift principles. This would represent a step down from the ideal system in the sense that it would not be able to trace the movement of the center of gravity but would rather be directly linked to the speed of a body segment.

FIGURE 1:

IDEAL VELOCITY RECORDING SYSTEM

Sprinter ⟷ Servo System/T.V. Camera

↓

Impulses

↓

FM Tape Recorder ⟶ Recorder for Immediate Graphic Record

↓

A-D Converter

↓

Computor ⟶ Print Out

In place of a non-contact device to record the speed of a particular body segment, it would be necessary to go to a mechanical link between the sprinter and the recording devices. Such a system could look like the one outlined in Figure 2.

The mechanical link to the recording devices could be a lightweight nylon cord which would drive a photoelectrical tachometer. The tachometer would be capable of generating a very large number of impulses per second and thus to record these without losing resolution would require a frequency modulated tape recorder. This would allow for storage of all raw data and subsequent playback at a slower speed into a recorder or into an A-D converter for input to a computor. Alternatively, the impulses could be fed into a rate meter to convert them to a voltage level which could be recorded. Ideally a high speed recording device would be necessary for the graphic portrayal of the data, such as the Honeywell visicorder. With such a system the only weak link would be the mechanical connection between the sprinter and the recording devices.

FIGURE 2:

ELECTRO-MECHANICAL SYSTEM

$$
\begin{tikzcd}
\text{Sprinter} & \text{Cord/Photoelectric Tachometer} \arrow[l] \arrow[d] & \\
& \text{Impulses} \arrow[r] \arrow[d] & \text{Rate Meter} \arrow[d] \\
& \text{FM Tape Recorder} \arrow[r] \arrow[d] & \text{Recorder for Immediate Graphic Record} \\
& \text{A-D Converter} \arrow[d] & \\
& \text{Computor} \arrow[r] & \text{Print Out}
\end{tikzcd}
$$

ELECTRO-MECHANICAL SYSTEM:

The chopper wheel should be light in weight (eg., aluminum spoke construction and as thin as possible); small in radius (this must be balanced by the number and size of slots needed); and have a small angular momentum (this conflicts with the need for a large number of impulses per meter). With these considerations in mind it should be possible to construct a system with very small inertia. For example, assume one wanted average speed over every one centimeter of the 100 meters, and further, that one wanted to average twenty-five impulses to get this average speed. This would require 2500 impulses per meter. With 100 slots in the chopper wheel it would have to turn 25 revolutions per meter. If each of the 100 slots were one millimeter in width with a one millimeter space between each, this would require a chopper wheel of twenty centimeters circumference or approximately sixty-four millimeters diameter. Assuming a maximum capability of twelve meters per second, there would be a maximum number of revolutions of 300 per second and a maximum number of impulses of 30,000 per second.

The drive shaft should be as light as possible, as small in diameter as possible and as short as possible. It must be supported by low friction bearings. The drive wheel on the shaft must provide for a non-slipping grip between the nylon cord and the shaft (probably the cord would have to take one turn around the drive wheel). There might also be a gear counter attached to the shaft to record every meter of revolution. Assuming the drive wheel

should turn 25 times per meter, this would require a wheel of 1.275 centimeters diameter.

A photocell on one side of the chopper wheel must be perfectly aligned with the one millimeter openings in the chopper wheel and must be shielded from the other openings. The photocell should be capable of responding to 100,000 impulses per second. The light source must be strong and constant and effectively shielded to illuminate only one slot at a time. The photocell impulses must be collected, amplified, squared, averaged, and a continuous signal given out to the recording device. As an example see Figure 3.

The system for containing the 120 meters of nylon cord must have a very small inertia and be capable of rewinding the 120 meters of cord in a convenient amount of time. A cord guide would be needed to rewind the cord onto the reel in a regular manner. For example, assume that the takeup reel will turn twenty-five times per meter. If the nylon cord was one millimeter then in twenty-five revolutions one meter of cord could be taken up. Using a reel 100 millimeters wide would accommodate four meters of cord in one width; thus approximately thirty layers of cord(three centimeters thick) would be wound on the reel.

A torque would be required to offset the angular momentum of the system. Thus the system should have some capability of slowing when the sprinter is slowing. A system of springs could be used to store kinetic energy

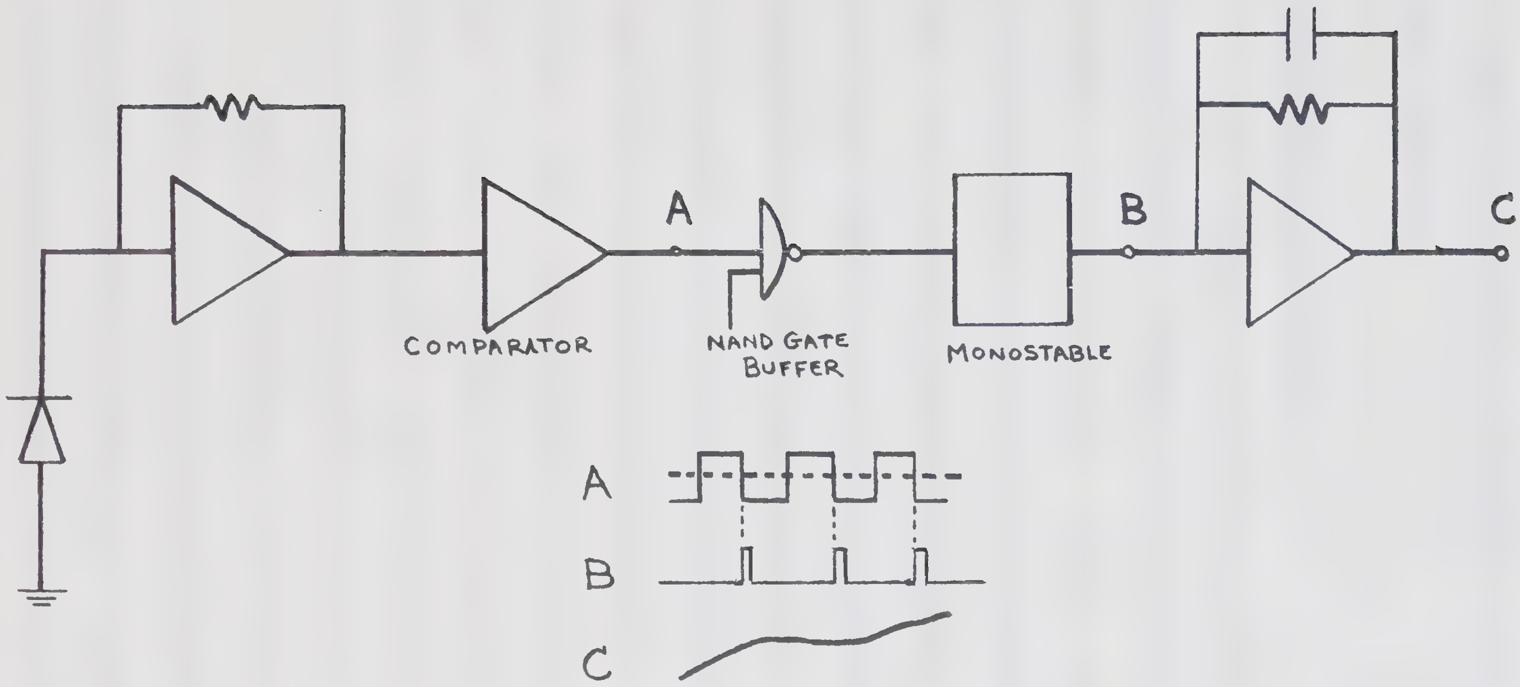


FIGURE 3:

AMPLIFICATION AND AVERAGING OF ELECTRICAL IMPULSES

and release it when appropriate to slow the system. The sprinter would have to apply an additional force to overcome the resistance of the springs, but using leverage principles it should be possible to keep these additional forces quite small.

MECHANICAL COMPONENTS:

All mechanical components have been machined out of lightweight aluminum, except the braking material, photodiode, insulation material, bearings, and axles (see Plate 2). The device was mounted on a $\frac{1}{4}$ inch plate of aluminum (a) and protected by a 1/8 inch plexiglass cover (b). The weight of the aluminum plate and electric rewind motor (c) was sufficient (10.45 kg.) to keep the device from moving during operation. A continuous strand (130 meters) of lightweight nylon cord (d) has been used as the mechanical link between the sprinter and the device. The cord was approximately one millimeter in diameter and had a 9.54 kilogram breaking capacity. There was approximately 1.76 percent stretch per kilogram of load. To overcome the inertia of the system the sprinter must exert a force of 0.155 kilograms. Once in motion the sprinter needed to exert only 0.135 kilograms to overcome the resistance of the system.

On leaving the device the cord ran under one guide and over a second (e). These guides were mounted on aluminum shafts with oilite bearings. The bearings allowed for small sideways movement of the cord. The shafts were connected and spring loaded. Their main purpose was to absorb jerks

as the sprinter left the blocks and throughout the run.

The heart of the device was the chopper wheel (f) with light source and photoelectric tachometer. The nylon cord took one complete turn around a drive wheel which was connected to the chopper. The drive wheel had a circumference of 40.0 millimeters and thus the drive wheel and chopper revolved twenty-five times per meter of cord pulled out by the sprinter. The chopper wheel had 100 one millimeter wide slots, spaced two millimeters apart around its circumference, and thus 2500 impulses were generated per meter. On one side of the chopper wheel mounted at the circumference was a six volt incandescent bulb (g). The bulb was shielded in a manner which allowed it to illuminate only one slot at a time. Opposite this light there was a photodiode (h) mounted on an insulating material (rulon). The leads to the photodiode were shielded by a microphone connector (k). The light source and photodiode were further shielded (l) from external light.

A takeup reel (m) was provided for storing 130 meters of cord. The reel was mounted on an axle with roller bearings. To rewind the cord a 1/15 H.P. electric motor was provided. The motor turned at 1750 R.P.M. and had a two to one ratio for turning the takeup reel (100 meters of cord could be rewound in approximately fifteen seconds). Engagement of the rewind gears was done manually with a third gear (n) mounted on a lever. When not in use the third gear remained disengaged due to its own weight.

To wind the cord on the reel in a regular manner, a manually operated guide (0) was provided. The guide was set in its center position when rewinding was complete.

To slow the chopper and takeup reel when the sprinter slowed a set of brakes (p) and (q) were provided. The brakes were levered in such a manner that the cord released them when pulled out and engaged them when tension in the cord was released. To achieve this effect the cord was fed through double tapered holes in shafts mounted across the lever arms of each brake. The rear brake (q) was angled upward and the front brake (p) was angled downwards. Tension on the cord caused both to move towards the horizontal position thus releasing the brakes.

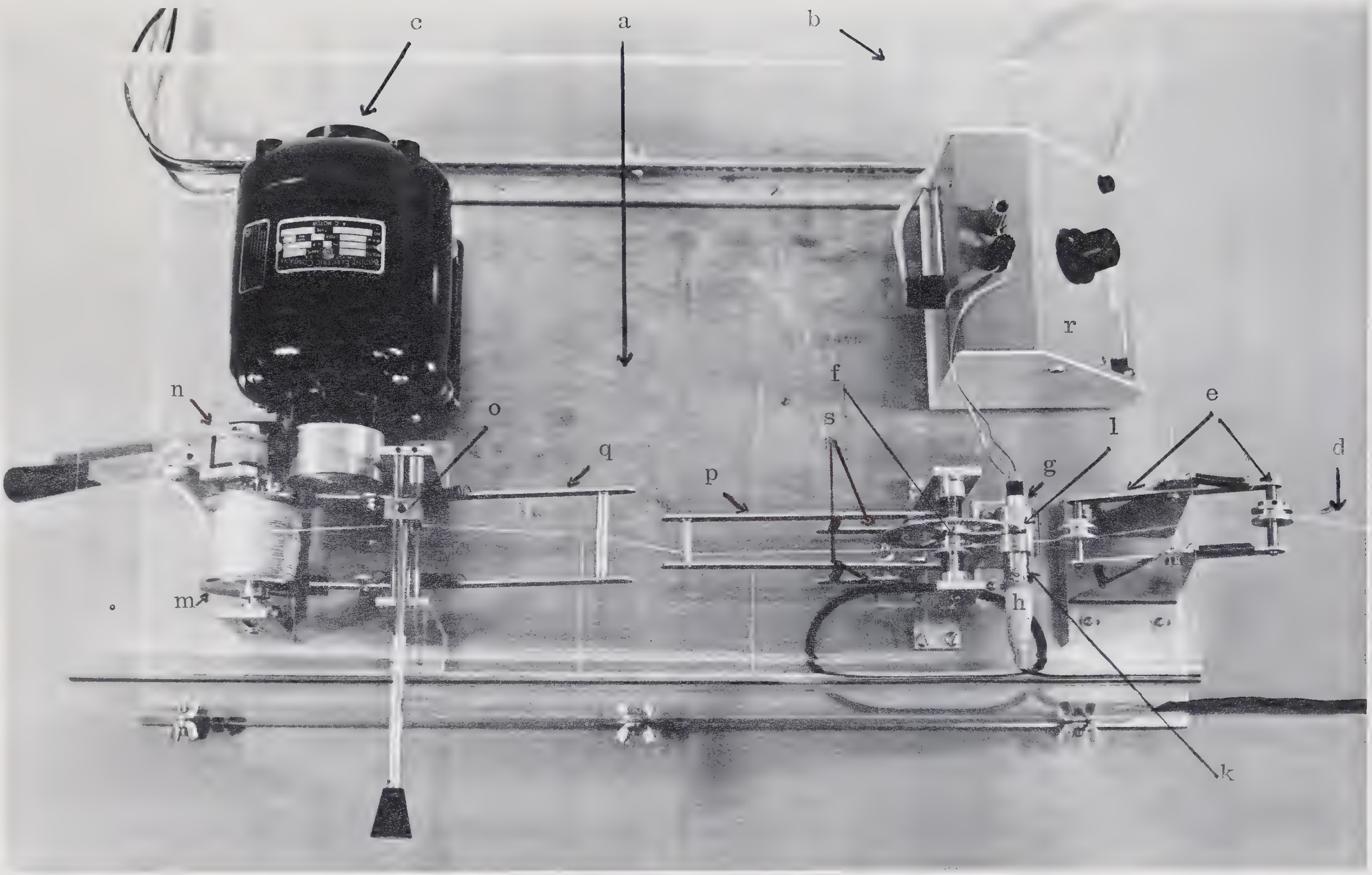


PLATE 2:

OVERHEAD VIEW OF INSTANTANEOUS VELOCITY RECORDER (MECHANICAL COMPONENTS)

ELECTRONIC COMPONENTS

A Heath direct current power supply (Plate 2, r) (0-35 volts) was provided for the six volt, 40 milliamp incandescent bulb.

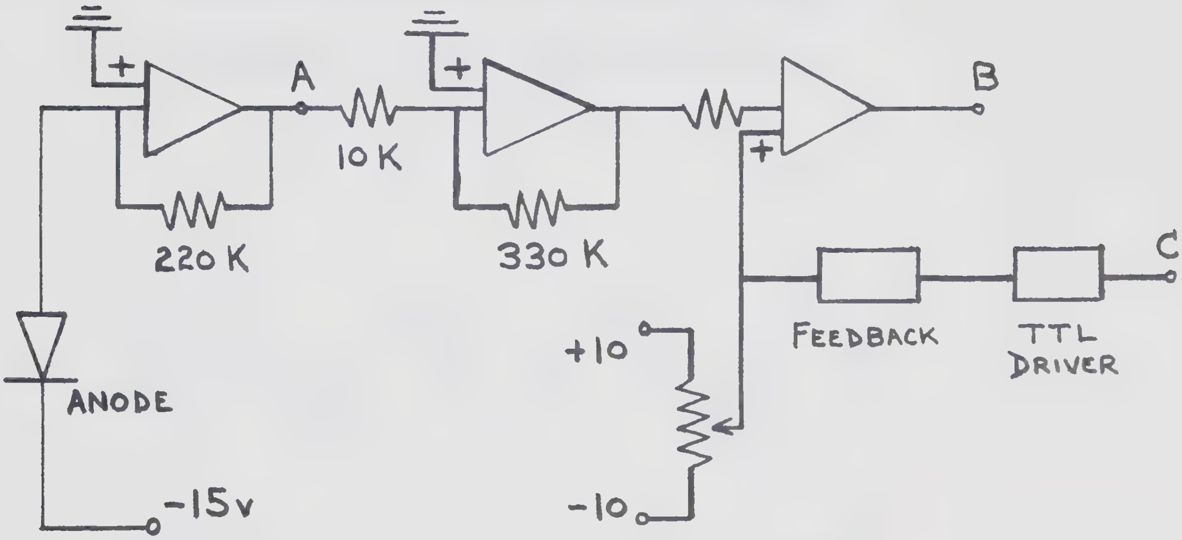
The Hewlett Packard #4220 photodiode (Plate 2, h) had a response time of less than one microsecond. The photodiode was run with a reverse bias of -15 volts. The signal was amplified through two operational amplifiers, and passed through a comparator (Heath, Model EU-800-HB) to square the signal (see Figure 4). This squared signal was then fed through a monostable to generate a constant sized pulse for every impulse (11 x 10.6 seconds). The output from the monostable was passed through an operational amplifier rate meter for conversion to a dc level output (see Figure 5). The circuits described in Figures 4 and 5 were patch wired using the Heath Analog Digital Designer. (see Figure 6 for the wave forms expected at the labelled points in Figures 4 and 5).

The resistance-capacitance time constant for the rate meter was 0.068 seconds. (see Figure 7 for the number of impulses that were averaged for speeds from one meter per second up to twelve meters per second.)

A 120 volt ac power source was provided to drive the dc power supply and the rewind motor.

FIGURE 4:

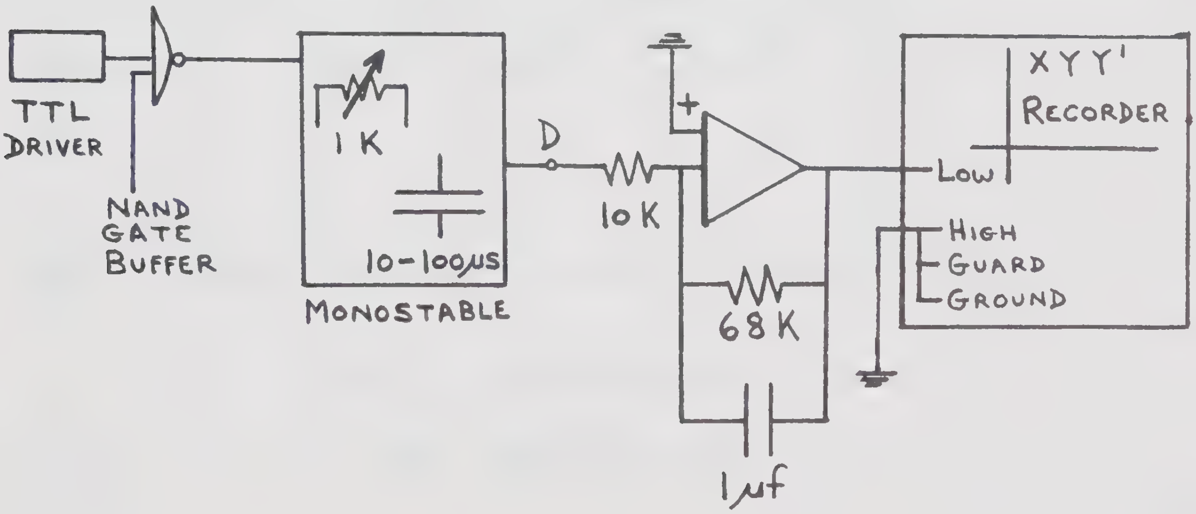
AMPLIFICATION AND SQUARING OF SIGNAL



(See Figure 6 for the wave forms expected at the labelled points A-D)

FIGURE 5:

OPERATIONAL AMPLIFIER RATE METER

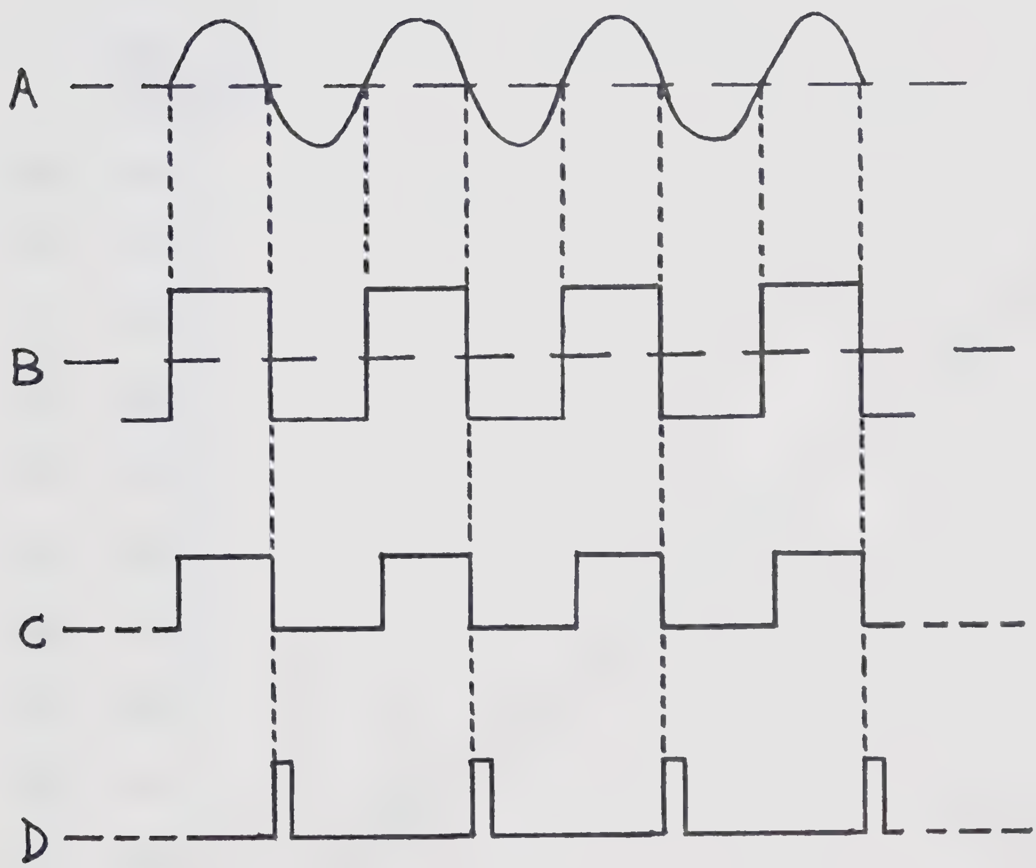


(See Figure 6 for the wave forms expected at the labelled points A-D)

FIGURE 6:

WAVE FORMS EXPECTED FROM

AMPLIFICATION AND SQUARING



A-C : FIGURE 4

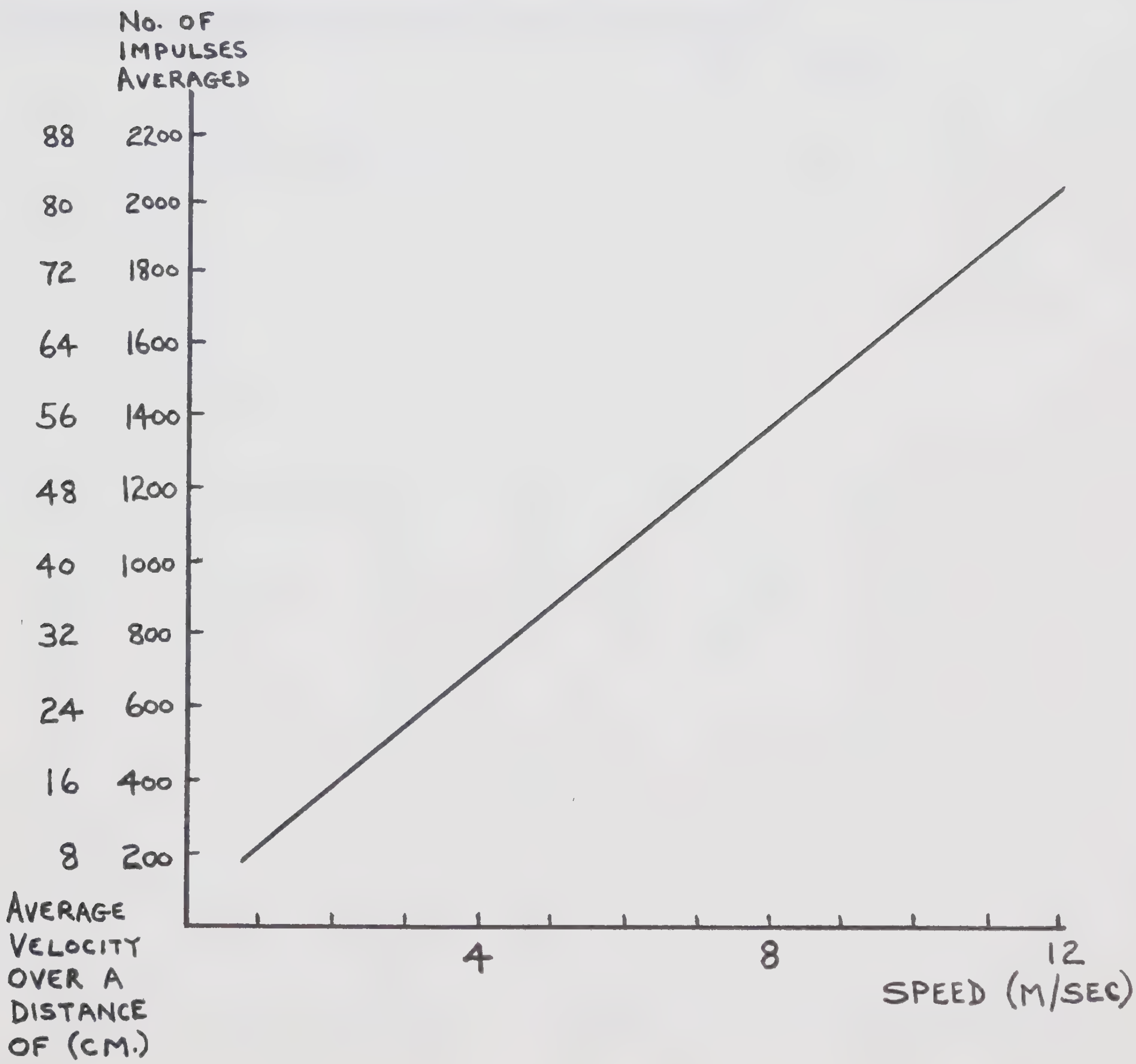
D : FIGURE 5

FIGURE 7:

NUMBER OF IMPULSES AVERAGED

VERSUS

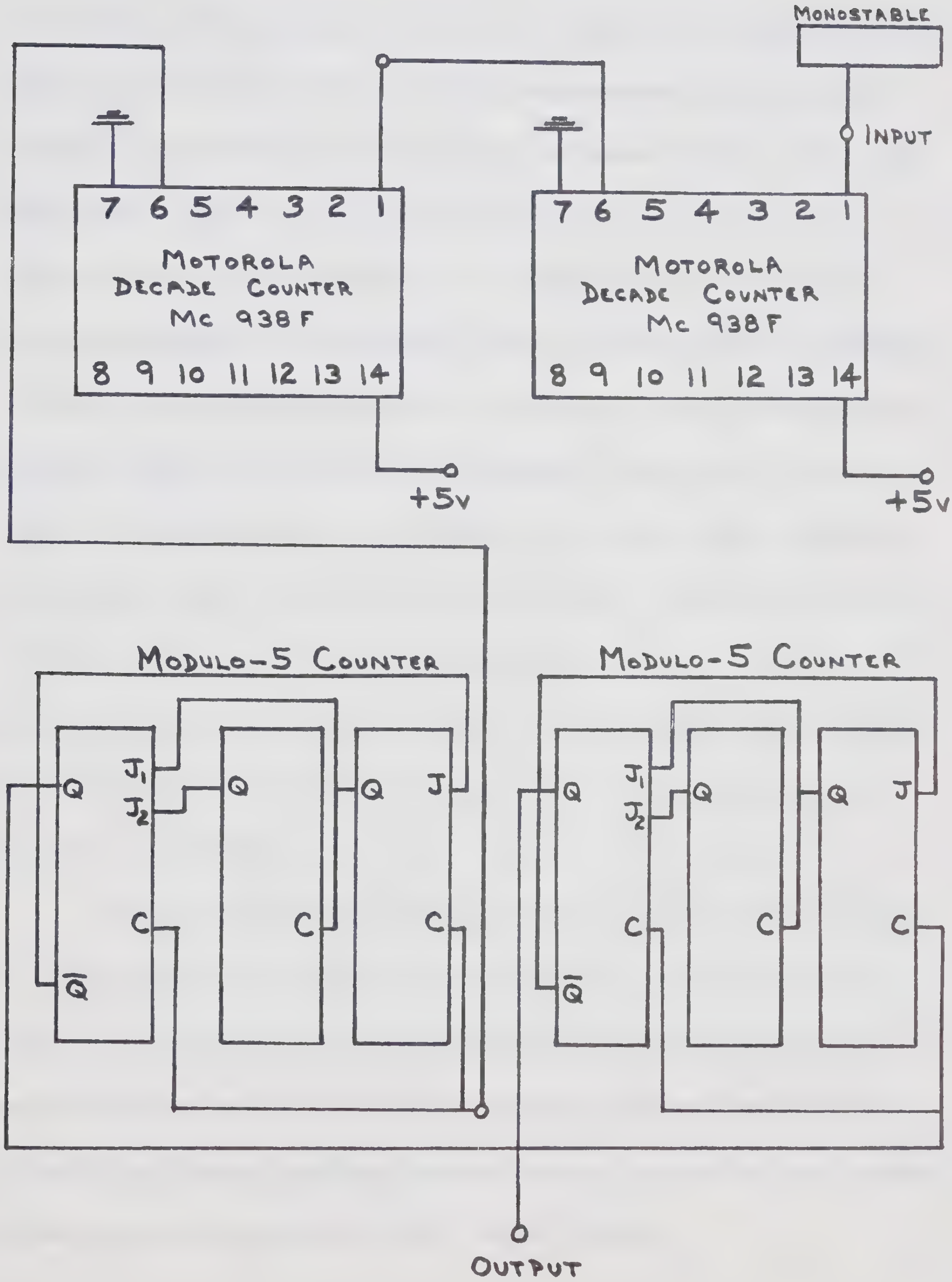
SPEED (METERS/SECOND)



A "divide by 2500" counting circuit (see Figure 8) was provided to count every meter of cord which was pulled out. This circuit worked off the same photodiode and amplification circuit described above. It consisted of two "divide by ten" circuits followed by two "divide by five" circuits. The "divide by ten" circuits (Motorola) were wired into the Heath Integrated Circuit Card (Model EU-50-MC); the "divide by five" circuits were patch wired using J-K flip flops (Heath, Model EU-800-CB).

FIGURE 8:

"DIVIDE BY 2500" COUNTER



RECORDING

A Honeywell Model 540 TM XYY' recorder was used. This device allowed for operation of one axis on a time sweep basis. In this instance the X axis was set to sweep at the rate of two centimeters per second which allowed for approximately nineteen seconds of recording time (thirty-eight centimeters). Thus one millimeter represented 0.05 seconds. The accuracy of the sweep was $\pm$ 1% of full scale. The output from the operational amplifier rate meter was connected to the Y axis with a full scale deflection of fifteen centimeters (twelve meters per second). Thus a one millimeter deflection represented 0.08 meters per second. This scale can accurately be read to 0.5 millimeters or 0.04 meters per second. The output from the "divide by 2500" counter was connected to the Y' axis and thus used as an event marker to count every meter of cord pulled out. Full scale deflection of this axis was approximately 0.5 centimeters. Pen response of the XYY' recorder was typically one second for a full scale deflection of twenty-five centimeters.

A remote switch at the 100 meter mark was connected for starting the sweep circuit of the X axis on the starter's "Set" command, and for resetting the sweep circuit as the sprinter crossed the 100 meter mark. To operate the Honeywell XYY' recorder remotely in this manner the X axis was set to the "sweep" position, the on-off control was in the "pen" position, and the reset-start control was in the "start" position.

CHAPTER III

EVALUATION OF VELOCITY RECORDER

It seemed desirable to set out, at the first, for the benefit of the reader in following through this chapter, what evaluation was necessary and how this evaluation was approached. Although validity and reliability could have been included as part of the evaluation of the electronic and mechanical components, the problem was set out into the four areas of electronic components, mechanical components, validity, and reliability.

The electronic components were expected to be extremely accurate, the only exception being the ability of the researcher to read the graph of the Honeywell XYY' recorder to better than 0.5 mm. (0.3% of full scale deflection). It was necessary to know the accuracy of the electronics and recording device independently of the chopper and light source, thus the following points were considered using a neon bulb of variable, but known, frequency.

1. A large range of frequency response from the photodiode was desired, along with an adequate signal level, in order to maintain resolution in recording velocity. This meant amplifying the signal from the photodiode with two operational amplifiers in order that frequency response could be maintained (since each only had to amplify one half as much).

2. Since eventually these amplified impulses were to be fed in, a sharp and well formed impulse was desirable. Thus a comparator was used to square the signal and a monostable was used to generate a small but constant sized pulse (varying the resistance and capacitance values in the monostable allowed this adjustment).

3. With increasing frequency any small amount of movement in the light source would cause the square waves from the comparator to overlap due to changes in the intensity of the signal. Thus it was necessary to adjust the reference voltage of the comparator to prevent this overlap.

4. The output from the rate meter had to be adjusted to average impulses over a certain time constant in order to match the pen response capability of the recording device. Varying the resistance and capacitance values in the rate meter allowed this adjustment.

5. The full scale deflection of the Honeywell recorder had to be set. Measuring the input frequency of the neon light exactly made it possible to adjust the recording scale.

6. Once full scale had been set, the linearity of the recording in response to different frequencies and the reading accuracy had to be determined.

7. The accuracy of the "divide by 2500' counting circuit had to be determined independently of the recording device, using a known input frequency and measuring the output of the circuit exactly.

8. An estimation of the reading error involved in the event marker axis had to be determined.

The mechanical components had all been machined and aside from any defect in material were expected to operate reliably. There remained two problems, however: - (1) to control the motion of the chopper and takeup reel by adjusting the tension in the brakes and - (2) once the first problem was solved, to measure the resistance of the system to a force exerted on the cord.

Under the heading of validity, the following points had to be considered: - (1) How accurately did the chopper and light source work independently of the cord driving the chopper? To evaluate this, the rewind motor was used to rotate the chopper. - (2) Using the cord to drive the chopper, did the system measure an applied and known velocity accurately? To determine the accuracy of the system, weights subject only to the force of gravity were dropped attached to the cord. This was an important test since the force being applied to the system would accelerate the weight very smoothly. If the system was capable of responding smoothly to a smooth force, then the expected uneven pattern of velocity of a sprinter

could be attributed entirely to the sprinter and not to the system.

The reliability of the velocity recorder was defined as the repeatability of the same measurements (dropping weights from various heights) on different occasions. Thus the error in measurement on one occasion was compared with the error in measurement on a separate occasion.

ELECTRONIC COMPONENTS

The initial problem encountered was one of maintaining adequate signal levels in conjunction with a large range of frequency response (0 - 30,000 impulses per second). The Hewlett Packard #4220 photodiode had a response time of less than one microsecond when run with a reverse bias of -15 volts. It was necessary to house the photodiode in a microphone connector and use shielded cable on the leads to cut down on noise pickup. It was further necessary to ground the microphone connector as well as use insulating material (rulon) for mounting the connector to the velocity recorder. The voltage output from the photodiode, so connected, was 0.1 - 0.2 volts as measured on an oscilloscope. Two operational amplifiers were used to amplify this output voltage up to a level of 5 - 6 volts. Experimentation was necessary in arriving at the values of the resistances in these two operational amplifiers which would maintain adequate signal impulses for the comparator stage which followed, bring the voltage level

to approximately 5 volts and still maintain a frequency response range of 0 - 30,000 impulses per second (See Figure 4). An operational amplifier-type comparator was used to square the amplified impulses and these were subsequently fed through a monostable to generate a constant size pulse for every impulse (11 x 10^{-6}seconds). The output from the monostable was connected to the operational amplifier rate meter for averaging (resistance-capacitance time constant 0.068 seconds) and conversion to a direct current output. This direct current output was fed directly to the Y axis of the XYY' recorder. The comparator reference voltage level could be varied by means of an external resistance from -10 volts to +10 volts. Control of this reference voltage level allowed for adjustment in the width of square wave output from the comparator and thus square waves could be prevented from overlapping due to small amounts of "jitter". A dual beam oscilloscope allowed monitoring of the amplified and squared signal for adjustment purposes. During the above procedure the photodiode was in close contact with a neon bulb from the Heath Binary Information Module. The light was connected to the squre wave output of a Heath Digital Timing Module. A Heath Digital Frequency Meter was also connected to the square wave output of the Digital Timing Module. Thus the exact frequency of the neon light was known and the full scale deflection of the XYY' recorder could be set.

Once the circuit was designed to operate from 0 - 30,000 impulses

per second and the full scale deflection of the XYY' recorder set, the following tables were constructed as a final check of the accuracy of the system and recording device. (See Table 1 and Table 2).

To obtain the results in Table 1 the impulses per second of the neon light were set using the digital frequency meter. A reading from the XYY' recorder was then taken. (Also see Figure 9).

For the results in Table 2 the XYY' recorder was set to specific levels and the exact frequency of the light source was then read from the digital frequency meter. (Also see Figure 9). A sample recording obtained during these procedures has been included in Appendix 1.

The results in Tables 1 and 2 substantiate the accuracy of the electronic circuitry and recording device independently of the chopper and light source used in the velocity recorder. It was found that reading error from the graph of the XYY' recorder was within 100 impulses (0.04 meters per second) and this was considered to be excellent resolution.

1	2					3				
Heath Digital Timing Module Setting	Heath Digital Frequency Meter Reading (x 1000)					Honeywell XYY' Recorder -Y Axis Reading (cm.)				
Hertz	1	2	3	4	5	1	2	3	4	5
0.1	0.000	0.000	0.000	0.000	0.000	0.0	0.0	0.0	0.0	0.0
1.0	0.001	0.001	0.002	0.001	0.001	0.0	0.0	0.0	0.0	0.0
10.0	0.011	0.010	0.012	0.010	0.010	0.0	0.0	0.0	0.0	0.0
100.0	0.100	0.101	0.101	0.094	0.102	0.05	0.05	0.05	0.05	0.05
1000.0	1.001	1.000	1.002	0.980	0.993	0.50	0.50	0.50	0.45	0.45
External Capacitor (500 pf)	2.011	2.004	2.006	1.993	2.001	1.00	1.00	1.00	1.00	1.00

1. The Heath Digital Timing Module multiplier dial was set to the positions indicated.

2. The Heath Digital Timing Module variable control was adjusted until the Heath Digital Frequency Meter indicated the desired light frequency.

3. Readings were taken from the graph paper of the Honeywell XYY' recorder (1 cm. represented 2000 impulses per second).

TABLE 1: - XYY' READINGS IN RESPONSE TO LIGHT FREQUENCY

1	2					3						
Heath Digital Timing Module Setting	Honeywell XYY' Recorder -Y Axis Setting (cm.)					Heath Digital Frequency Meter Readings (x 1000)						
Hertz	1	2	3	4	5	1	2	3	4	5	Mean	Standard Deviation
External Capacitor (Variable)	2.0	2.0	2.0	2.0	2.0	4.013	4.007	4.039	4.006	3.974	4.007	± 0.023
"	4.0	4.0	4.0	4.0	4.0	8.004	8.023	8.068	8.011	7.983	8.017	± 0.032
"	7.5	7.5	7.5	7.5	7.5	14.933	15.001	15.056	14.970	15.038	14.999	± 0.044
"	12.55	12.5	12.5	12.55	12.55	25.104	25.074	25.022	25.180	25.050	25.046	± 0.032
"	14.0	14.0	14.0	14.0	14.05	28.022	28.005	27.979	28.057	28.139	28.020	± 0.028
"	15.0	15.0	15.0	15.0	15.0	30.087	30.015	30.003	29.994	29.958	30.011	± 0.044

1. The Heath Digital Timing Module multiplier dial was set to the positions indicated.
2. The Heath Digital Timing Module variable control was adjusted until the Honeywell XYY' recorder Y axis indicated the desired setting. (1 centimeter represented 2000 impulses per second.)
3. Readings were taken from the Heath Digital Frequency Meter.

TABLE 2 - FREQUENCY READINGS FOR DIFFERENT XYY' RECORDER SETTINGS

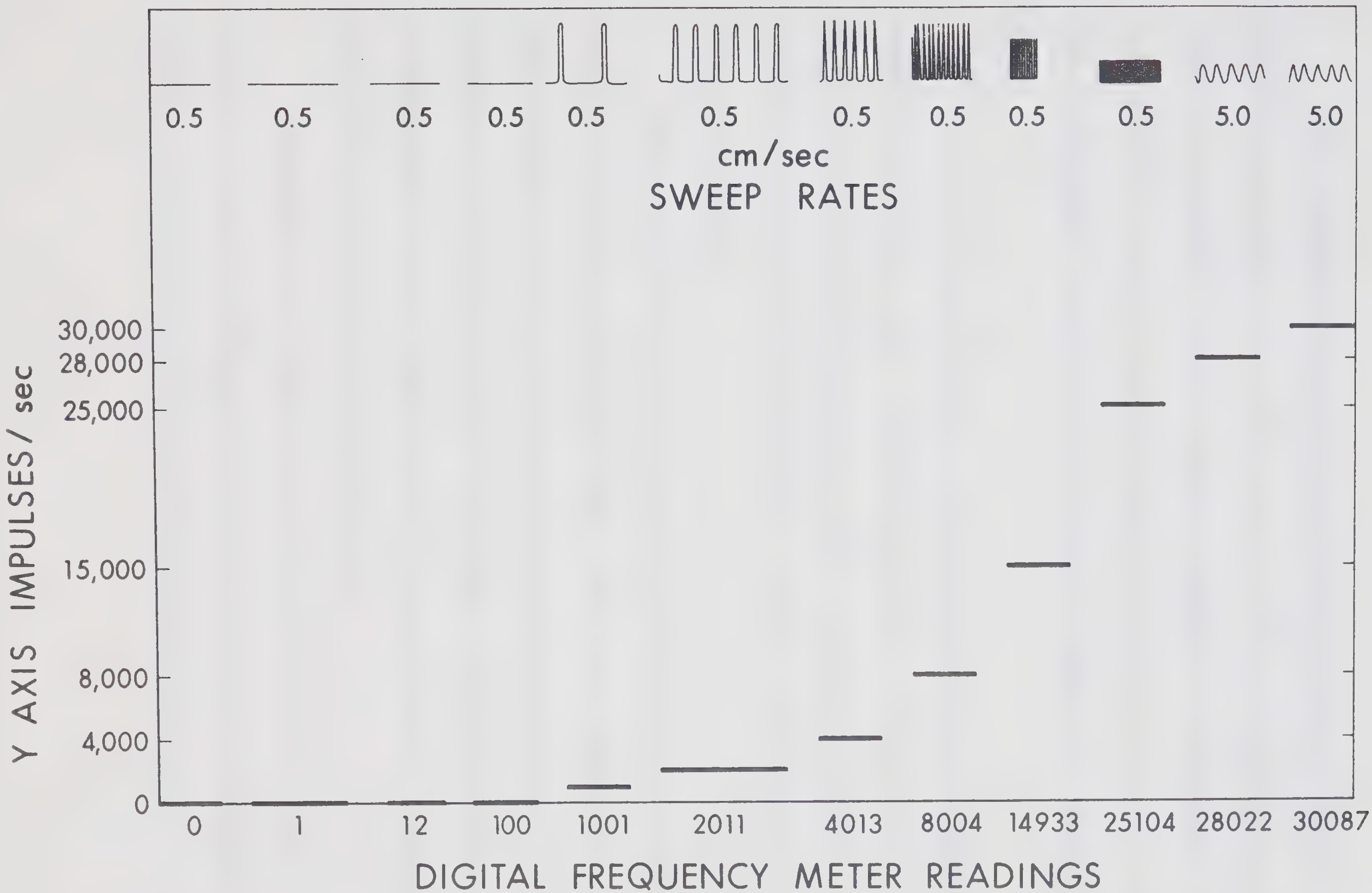


FIGURE 9:
CALIBRATION USING NEON LIGHT AND HEATH DIGITAL FREQUENCY METER

The impulses from the monostable were also fed into a "divide by 2500" counter (See Figure 8) whose output was connected to the Y axis of the XYY' recorder. Since 25 revolutions of the wheel corresponded to 1 meter of cord pulled out, then 2500 impulses occurred every meter. Thus this "divide by 2500" counter provided a means of counting every meter of cord.

Table 3 tabulates the results of feeding a known frequency (Heath Digital Timing Module square wave output) through the "divide by 2500" counter and recording the output of the counter as indicated by the Heath Digital Frequency Meter. As expected, the "divide by 2500" counter was 100 percent accurate.

The results in Table 4 were collected at the same time as Tables 1 and 2, under the same experimental setup. This Table compares the obtained distance between event marks with the theoretical distance. It appeared that the only error in the event marker occurred as a result of reading error from the graph of the XYY' recorder (since the "divide by 2500" counting circuit was 100 percent accurate).

In summary, as a result of data collected in Tables 1 to 4, the only error resulted from difficulty in reading the scale of the graph paper of the XYY' recorder to better than one-half millimeter accuracy.

1	2			3			
Heath Digital Timing Module Setting	Input: Heath Digital Frequency Meter Readings x 1000			Output: Heath Digital Frequency Meter Readings X 1000			% Error
Hertz	1	2	3	1	2	3	
External Capacitor (Variable)	2.5	2.5	2.5	1	1	1	0
	5.0	5.0	5.0	2	2	2	0
	7.5	7.5	7.5	3	3	3	0
	10.0	10.0	10.0	4	4	4	0
	12.5	12.5	12.5	5	5	5	0
	15.0	15.0	15.0	6	6	6	0
	17.5	17.5	17.5	7	7	7	0
	20.0	20.0	20.0	8	8	8	0
	22.5	22.5	22.5	9	9	9	0
	25.0	25.0	25.0	10	10	10	0
	27.5	27.5	27.5	11	11	11	0
	30.0	30.0	30.0	12	12	12	0

1. The Heath Digital Timing Module multiplier control was set to the position indicated.

2. The Heath Digital Timing Module variable control was adjusted to give the desired frequency as indicated by the Heath Digital Frequency Input Meter.

3. The output of the "divide by 2500" counter was recorded as indicated by the Heath Digital Frequency meter.

TABLE 3:

ACCURACY OF "DIVIDE BY 2500" COUNTER

1	2			3	4	5			6	7
Heath Digital Timing Module Setting	Heath Digital Frequency Meter Readings x 1000			X axis sweep rate cm/sec.	Y axis mm. peak to peak theor-etical	Y axis mm. peak to peak actual			Diff-erence	% error
Hertz	1	2	3			1	2	3		
0.1	0.000	0.000	0.000	0.5	125,000	0	0	0		
1.0	0.001	0.001	0.002	0.5	12,500	0	0	0		
10.0	0.011	0.010	0.012	0.5	1,250	0	0	0		
100.0	0.100	0.101	0.101	0.5	125	125	125	125		
1000.0	1.001	1.000	1.002	0.5	12.5	12.5	12.5	12.5		
External Capacitor	2.011	2.004	2.006	0.5	6.25	6.25	6.25	6.25		
"	4.013	4.007	4.039	0.5	3.125	3.0	3.0	3.0	0.125	4.0
"	8.004	8.023	8.068	0.5	1.56	1.5	1.5	1.5	0.06	3.8
"	14.933	15.001	15.056	0.5	0.835	0.75	0.75	0.75	0.085	10.2
"	25,104	25.074	25.022	0.5	0.50	0.5	0.5	0.5		
"	28.022	28.005	27.070	5.0	4.45	4.5	4.5	4.5	0.05	1.1
"	30.087	30.015	30.003	5.0	4.15	4.0	4.0	4.0	0.15	3.6
										4.5% Average Reading Error

1. The Heath Digital Timing Module multiplier control was set to the positions indicated. 2. The Heath Digital Timing Module variable control was adjusted until the desired reading on the Heath Digital Frequency Meter was obtained. 3. The Honeywell XYY' recorder X axis was set to sweep at the rates indicated. 4. Based on the known frequency and the sweep rate the theoretical distance between event mark peaks could be calculated. 5. The actual distance between peaks on the Y' axis of the Honeywell XYY' recorder graph paper was measured.

TABLE 4: ACTUAL VERSUS THEORETICAL DISTANCE BETWEEN EVENTS AT DIFFERENT FREQUENCY LEVELS

MECHANICAL COMPONENTS

Since all parts were machined, only the following small adjustments were necessary:

The takeup reel and chopper wheel were adjusted in height to obtain sufficient deflection of the brakes from the horizontal (See Plate 2, p and q). This deflection of the brakes from the horizontal was required so that tension in the cord would tend to move them towards the horizontal and thus release them. Some experimentation with spring tension was also necessary in order to slow both wheels in the shortest amount of time, and yet, maintain the force that the sprinter must exert to overcome their resistance at the lowest level practical. Tension in the springs of the chopper wheel could be increased by positioning the lever arms (See Plate 2, s) at a lower level. Tension in the springs of the takeup reel could be increased by inserting the ends of the springs into holes further up the brake arms (See Plate 2, q). It was found necessary during rewinding of the cord, that the rear brake (q) be held free of the takeup reel. Weights were hung from the end of the cord once these adjustments had been made and it was found that 155 grams were required to start the cord and 135 grams were required to keep it in motion.

VALIDITY

The electronic circuitry had been tested and the XYY' scales

calibrated independently of the chopper wheel and light system as previously described. The problem remained therefore of validating the impulse system of the velocity recorder; first, independently of the cord and, second, with the cord.

The rewind motor was positioned to drive the chopper wheel using a solid rubber drive belt at an advantage of 8:1. Since the rewind motor turned at 1725 RPM this meant that the photodiode should detect approximately 23,000 impulses per second. (8 x 1725 RPM x 100 slots $\div$ 60 seconds) (See Figure 10 for the results of this test and see Appendix 1 for an actual recording).

The Heath Digital Frequency Meter was also monitoring the impulses of the photodiode and the figures on the graph represent readings taken at different intervals. At this point it was found that the 6 volt 40 milliamp light being used was not of sufficient intensity to obtain the complete range of 0 - 30,000 impulses per second. Thus it was necessary to operate the light at approximately 12 volts and 45 milliamps. At this intensity light bulbs were found to last 1 - $1\frac{1}{2}$ minutes, depending on the individual quality of the bulb. The above calibration procedure therefore was used whenever a new light bulb was inserted.

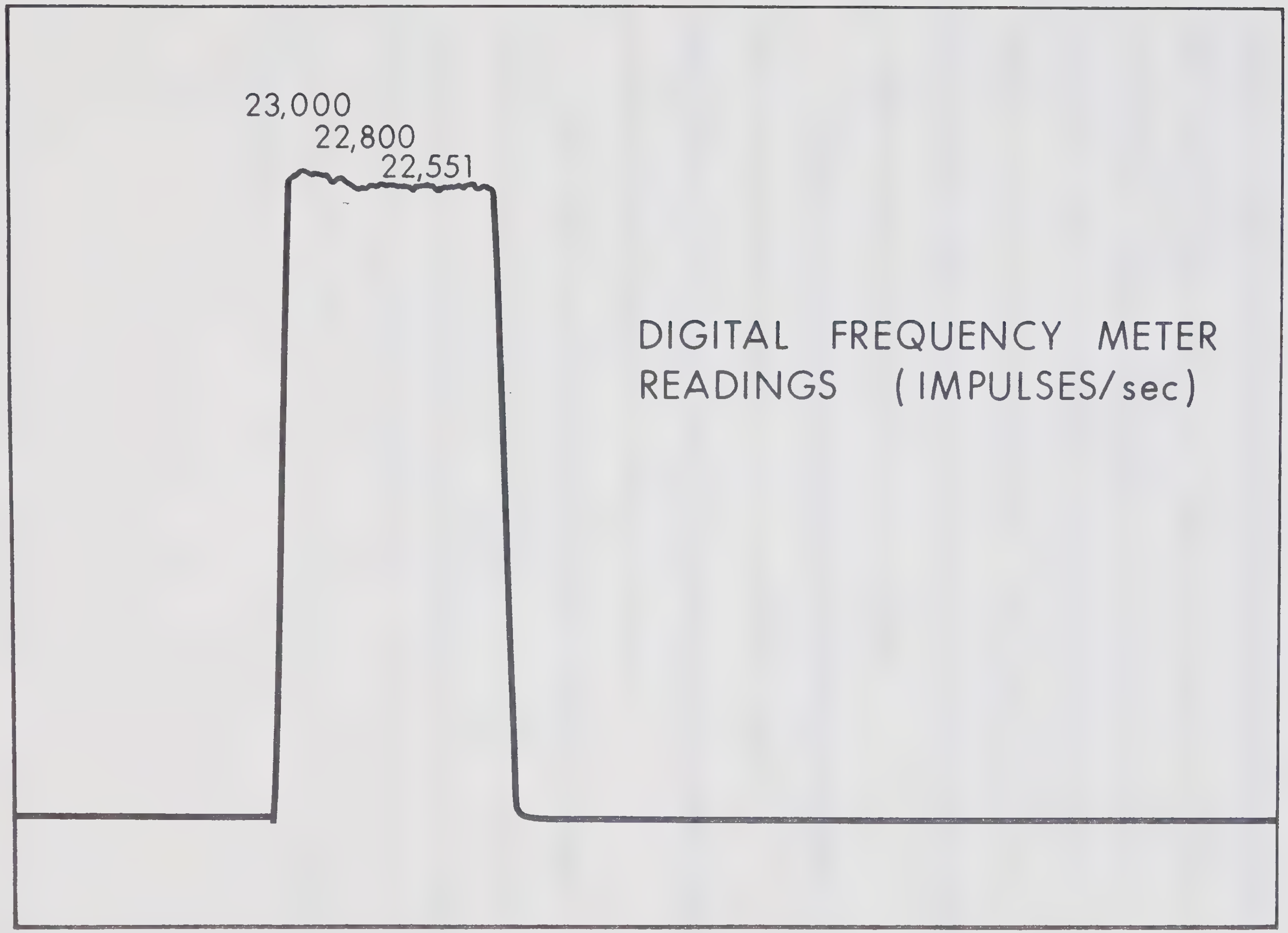


FIGURE 10: - VALIDATION OF IMPULSE SYSTEM INDEPENDENTLY OF CORD DRIVE

To test the validity of the impulse system using the cord drive, weights were attached to the cord and allowed to fall from different heights subject only to the force of gravity. (Figure 11 corresponds to a weight of 1.875 kilograms dropped from the height of 9.88 meters.) (Figure 12 represents a weight of 0.250 kilograms dropped from a height of 0.889 meters.) Since the weight was subjected to a known force (gravity), the experimentally obtained velocity could be compared to a theoretical velocity for estimation of the accuracy of the velocity recorder.

The above procedure was repeated from several heights and the results are recorded in Table 5 for the 1.875 kilogram weight and in Table 6 for the 0.250 kilogram weight. (A sample recording obtained from each height for each weight may be found in Appendix 2.)

Stopwatch times for each drop were also recorded. Percentage error of the experimental recording from the theoretical velocity has been calculated, basing the theoretical velocity on the known distance the weight fell and the time required to fall that distance. This time was obtained from the X axis of the XYY' recorder and was found to closely correspond to stopwatch time.

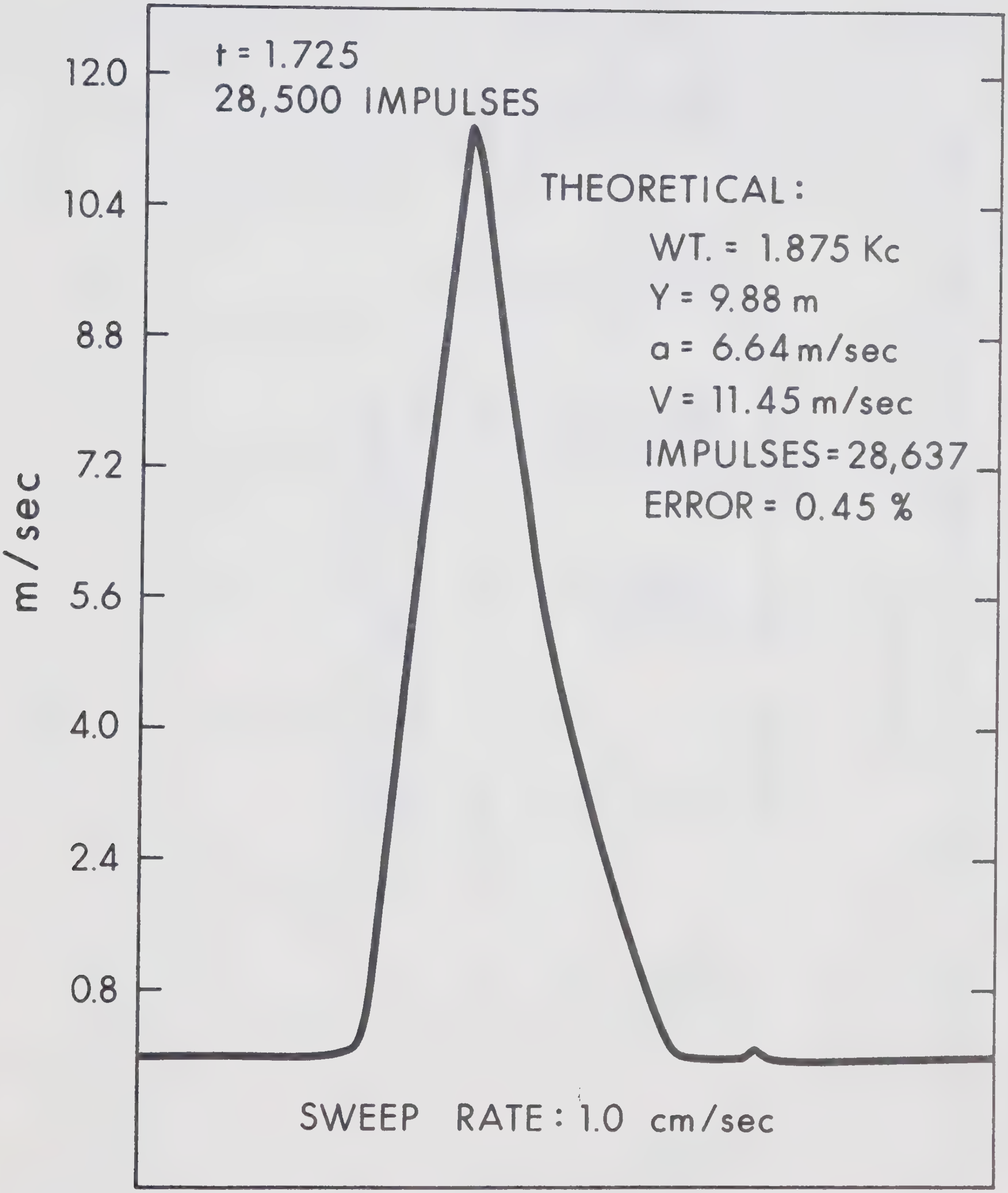


FIGURE 11:

VALIDATION OF IMPULSE SYSTEM USING CORD DRIVE AND 1.875 kg. WEIGHT FROM THE HEIGHT OF 9.88 METERS

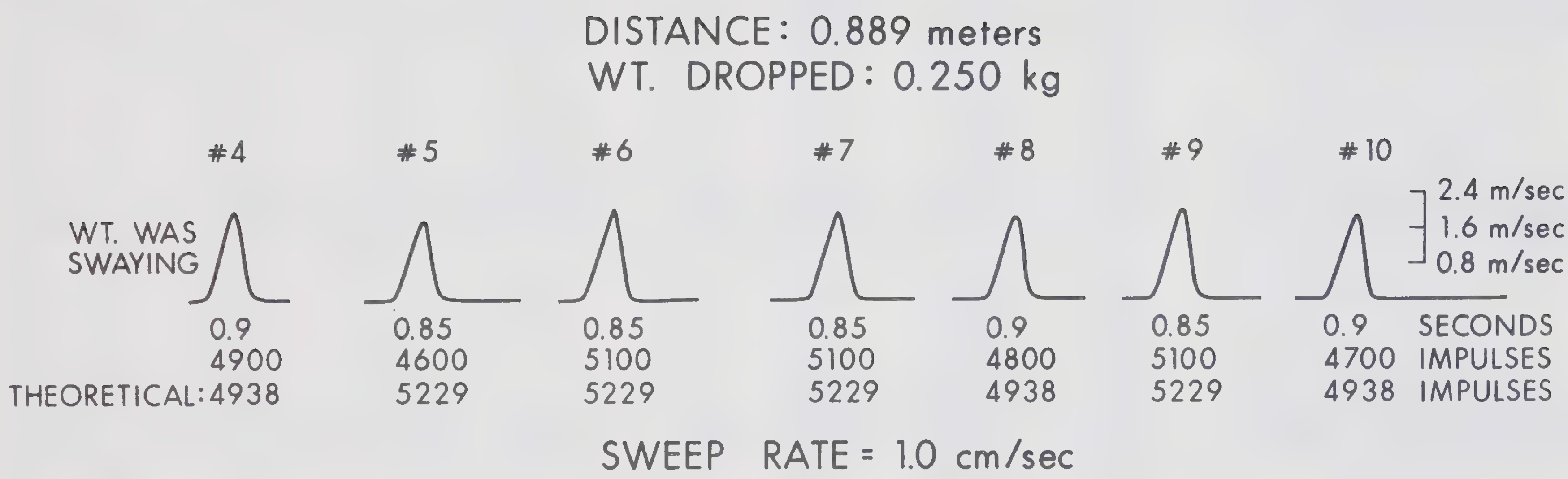


FIGURE 12:

VALIDATION OF IMPULSE SYSTEM USING CORD DRIVE AND 0.250 kg. WEIGHT FROM THE HEIGHT OF 0.889 METERS

Trial	Distance Dropped (Meters)	Stop-watch time (seconds)	Recorder Time (seconds)	Theoretical Acceleration (M/sec.^{2})	Theoretical Velocity M/sec.	Theoretical Impulses/Second	Recorded Impulses	Difference Impulses M/sec.	Difference M/sec.	% Error	# of Events	Event Marker Error (Meters)
1	0.819	0.6	0.525	5.94	3.12	7800	8100	300	0.12	3.8	1.25	
2	"	0.4	0.55	5.42	2.98	7446	8300	900	0.36	12.8	0.6	
3	"	0.6	0.525	5.94	3.12	7800	8200	400	0.16	3.8	0.9	
4	"	0.6	0.5	6.55	3.28	8190	8100	100	0.04	1.2	1.25	
5	"	0.6	0.5	6.55	3.28	8190	8200	10	0.004	0.12	1.25	
AVE	"	0.56	0.52	6.08	3.16	7885	8180	342	0.137	4.34	1.05	+0.231
1	3.78	1.2	1.05	6.865	7.2	18007	17100	900	0.36	5.0	3.75	
2	"	1.1	1.075	6.54	7.0	17581	17400	200	0.08	1.1	4.0	
3	"	1.0	1.05	6.865	7.2	18007	18400	400	0.16	2.2	4.25	
4	"	1.2	1.05	6.865	7.2	18007	17400	600	0.24	3.3	4.0	
5	"	1.2	1.05	6.865	7.2	18007	17800	200	0.08	1.1	3.5	
AVE	"	1.14	1.055	6.800	7.163	17926	17620	460	0.184	2.54	3.8	+0.02
1	6.83	1.6	1.55	5.67	8.8	22032	21800	200	0.08	0.9		
2	"	1.6	1.5	6.07	9.11	22760	21600	1100	0.44	4.83		
3	"	1.5	1.475	6.28	9.26	23152	22400	700	0.28	3.02	6.0	
4	"	1.5	1.6	5.32	8.6	21500	22100	600	0.24	2.8	7.25	
5	"	1.6	1.475	6.28	9.26	23152	22400	700	0.28	3.02		
AVE	"	1.56	1.532	5.924	9.01	22519	22060	660	0.264	2.92	6.625	-0.205
1	9.88	1.8	1.8	6.098	10.98	27444	27600	200	0.08	0.73	9.0	
2	"	1.8	1.725	6.644	11.45	28637	27900	700	0.28	3.02	8.75	
3	"	1.8	1.725	6.644	11.45	28637	28500	100	0.04	0.35	9.0	
4	"	1.8	1.775	6.27	11.13	27830	26900	900	0.36	3.6	9.0	
5	"	1.8	1.725	6.644	11.45	28637	26700	1900	0.76	6.6	8.25	
AVE	"	1.8	1.75	6.46	11.29	28237	27500	760	0.304	2.86	8.8	-1.08

TABLE 5:
VALIDATION OF IMPULSE SYSTEM USING CORD DRIVE AND 1.875 KG. WEIGHT

Trial	Distance Dropped (Meters)	Stop-watch time (seconds)	Recorder Time (seconds)	Theoretical Acceleration (M/sec.^{2})	Theoretical Velocity M/sec.	Theoretical Impulses/ Second	Recorded Impulses	Difference Impulses M/sec.	Difference M/sec.	% Error	# of Events	Event Marker Error (Meters)
1	0.889	1.0	0.85	2.461	2.092	5229	5000	200	0.8	3.8	0.75	
2	"	1.0	0.85	2.461	2.092	5229	5000	200	0.8	3.8	0.75	
3	"	1.0	0.9	2.195	1.976	4938	4900	38	.01	0.5	0.75	
4	"	1.0	0.9	2.195	1.976	4938	4900	38	.01	0.5	1.0	
5	"	0.8	0.85	2.461	2.092	5229	4600	600	.24	11.4	1.1	
6	"	0.8	0.85	2.461	2.092	5229	5100	100	.04	1.9	1.25	
7	"	0.8	0.85	2.461	2.092	5229	5100	100	.04	1.9	1.5	
8	"	1.0	0.9	2.195	1.976	4938	4800	100	.04	2.0	1.5	
9	"	1.0	0.85	2.461	2.092	5220	5100	100	.04	1.9	0.75	
10	"	0.8	0.9	2.195	1.976	4938	4700	200	.08	4.0	1.0	
AVE.	0.889	0.92	0.87	2.35	2.05	5113	4920	187	0.066	3.17	1.03	+.141
1	4.15	2.0	1.8	2.56	4.61	11527	10600	900	0.36	7.8	4.2	
2	"	1.8	1.8	2.56	4.61	11527	10400	100	0.04	0.8	4.5	
3	"	1.8	1.755	2.69	4.73	11831	11800	31	0.01	.21	4.05	
4	"	1.8	1.755	2.69	4.73	11831	11600	200	0.08	1.6	4.0	
5	"	1.7	1.755	2.69	4.73	11831	11500	300	0.12	2.5	4.4	
AVE.	4.15	1.82	1.773	2.64	4.68	11686	11380	306	.122	2.58	4.28	+.13

TABLE 6:

VALIDATION OF IMPULSE SYSTEM USING CORD DRIVE AND 0.250 KG.WEIGHT or 0.235 KG. WEIGHT

From the results in Tables 5 and 6, average errors were computed. The velocity recorder, over 35 trials at different heights and with two different weights, was found to underestimate the theoretical velocity by 338 impulses per second or 0.134 meters per second. This corresponded to an average error of -1.62%, provided the direction of the error was taken into account. Without taking the direction of the error into account, the velocity recorder was found to err by 452 impulses per second, or 0.180 meters per second, from the theoretical values. This corresponded to an average error of 3.07%. In either case, the error was well within the accuracy to which the theoretical value for the velocity could be calculated and thus it was felt that the velocity recorder was extremely accurate.

The event marker error was also determined from Tables 5 and 6. It was found that over 35 trials that if the direction of the error were taken into account, the velocity recorder underestimated the actual distance by 0.127 meters over an average distance of 4.39 meters, which corresponded to a 2.86% error (2.86 meters underestimation in 100 meters). If the direction of the error were not taken into account, then the error in estimating the actual distance was 0.301 meters over an average distance of 4.39 meters or 6.8%.

There were several possibilities which could have accounted for these small amounts of error. One would expect that the theoretical velocity

would be underestimated by the velocity recorder since the rate meter yielded average speeds over a time constant of 0.068 seconds. Thus the final velocity recorded would represent the average velocity over the last one or two time constants. It was difficult to put a figure on the amount of underestimation from this source but it would be of the order of about - 1%. Although the dropping of the weights was relatively standardized, it was not mechanically controlled and therefore there could be as much as 0.25% error in the distance dropped or as much as 0.75% error in assuming that the initial velocity of the weight was zero. Since 28 out of 35 trials underestimated the theoretical velocity, taking the direction of the error into account would seem reasonable, and further, it would be possible to account for this underestimation with the above reasons. It would be likely that a positive initial velocity was imparted to the weight when released in the cases where the recorded velocity overestimated the theoretical velocity.

It should not be overlooked that the error in the event marker and the velocity axis were connected, since both obtained their impulses from the same photodiode and chopper. The close agreement between the experimental errors would substantiate this. There were other possibilities that might account for the error in the event marker (and thus perhaps the velocity) that could be mentioned. If the cord slipped approximately 3% in turning the chopper this would account very nicely for the errors in both

the event marker and the velocity recording. Some slippage may have occurred but it is unlikely that it amounted to 3%, due to other viable reasons offered to explain the error.

There might be some accumulative error in the event marker, based on the degree of precision of the diameter of the drive wheel around which the cord wraps to turn the chopper. It was machined to 12.75 millimeters diameter which, to four figures of accuracy, would yield a circumference of 40.03 millimeters and 24,981 impulses per meter. Accumulating the error over 100 meters would result in an underestimation of the distance by 0.76 meters. If the tolerance in the machining of the drive wheel were $\pm$ 0.02 millimeters, then the error could vary from an overestimation of 0.68 meters to an underestimation of 2.44 meters. There was the further possibility that the distance might be overestimated due to a smaller diameter of drive wheel and that the cord might be slipping to compensate. Many combinations of error are possible but the important point was that the overall error was something less than 3%.

Knowing the resistance of the velocity recorder (135 grams) and the weight dropped (0.250 kilograms or 1.875 kilograms) it was possible to calculate a theoretical value for the acceleration of the weights due to gravity from the formula $A = \frac{m_2 - m_1}{m_1 + m_2} \cdot G$; where A was the theoretical acceleration, m_2 was the weight dropped, m_1 was the resistance of the system, and G was the acceleration due to gravity. These results are compared with the experimentally obtained values in Table 7.

The discrepency with the heavier weight and the faster speeds could possibly be due to increasing resistance of the system at higher speeds as it was not possible to measure the resistance of the velocity recorder at these higher speeds. This is the most likely explanation since the stopwatch times for each occasion that the weight was dropped agreed so closely with the experimentally recorded times. Based on the theoretical acceleration as calculated in Table 7, the time to fall each distance should have been much faster than it in fact was; again indicating that the weight was falling slower due to some additional factor (resistance). An increase in the resistance of the system from 0.135 kg. to 0.400 kg. would be sufficient to eliminate all discrepancy in the case of the 1.875 kg. weight. An increase to 0.150 kg. would more than eliminate the discrepancy with the 0.250 kg. weight.

Weight Dropped	Resistance of System	Theoretical Acceleration	Average Experimental Acceleration	Discrepancy
1.875 kg.	0.135 kg.	8.838 m/sec.^{2}	6.316 m/sec.^{2}	25%
0.250 kg.	0.135 kg.	2.842 m/sec.^{2}	2.495 m/sec.^{2}	12.4%

TABLE 7:

THEORETICAL VERSUS EXPERIMENTAL ACCELERATION

RELIABILITY

Reliability in reference to the velocity recorder was defined as the repeatability of velocity measurements made on a separate occasion but under an identical experimental setup. The 1.875 kg. weight was dropped from the same heights as in Table 5 and the results were recorded in Table 8. The overall average error in the velocity recordings was 2.64% compared with the average error of 3.07% on the early occasion, when the direction of the error was disregarded. Taking the direction of the error into account, the error calculated from Table 8 was -1.19% compared with the previously tabulated error of -1.62%. A t test was performed on the values of 2.64% and 3.07% error and no significant difference was found between these average errors at the 0.05 level of significance.

The event marker had a -2.63% error when the direction of error was considered (compared with -2.86% previously) and a 6.2% error when the direction of error was not considered (compared with 6.8% previously).

On the basis of this data, it was concluded that the velocity recorder had good reliability (95%).

Trial	Distance Dropped (Meters)	Stop-watch time (seconds)	Recorder Time (Seconds)	Theoretical Acceleration ($M/sec.^2$)	Theoretical Velocity M/sec.	Theoretical Impulses/Second	Recorded Impulses	Difference Impulses	Difference M/sec	% Error	# of Events	Event Marker Error (Meters)
1	0.819	0.6	0.525	5.94	3.12	7800	7900	100	0.04	1.28	0.75	
2	"	0.6	0.55	5.42	2.98	7446	7800	350	0.14	4.69	0.75	
3	"	0.5	0.525	5.94	3.12	7800	7900	100	0.04	1.28	1.25	
4	"	0.6	0.525	5.94	3.12	7800	7900	100	0.04	1.28	0.75	
5	"	0.5	0.55	5.42	2.98	7446	7900	450	0.18	6.0	1.25	
AVE	"	0.56	0.535	5.73	3.06	7658	7880	220	0.088	2.91	0.95	+0.131
1	3.78	1.1	1.075	6.54	3.78	17581	17300	300	0.12	1.1	3.75	
2	"	1.0	1.075	6.54	3.78	17581	17100	500	0.20	2.85	3.25	
3	"	1.0	1.075	6.54	3.78	17581	17600	20	0.008	0.11	3.25	
4	"	1.0	1.075	6.54	3.78	17581	17300	300	0.12	1.1	4.0	
5	"	1.1	1.075	6.54	3.78	17581	17300	300	0.12	1.1	4.0	
AVE	"	1.04	1.075	6.54	3.78	17581	17320	284	0.114	1.25	3.1	-0.130
1	6.83	1.6	1.45	6.49	9.42	23551	21900	1600	0.64	6.79	5.5	
2	"	1.5	1.475	6.28	9.26	23152	23200	50	0.02	0.22	6.0	
3	"	1.5	1.475	6.28	9.26	23152	22900	200	0.08	0.86	6.0	
4	"	1.6	1.45	6.49	9.42	23551	23400	100	0.04	0.46	6.0	
5	"	1.4	1.475	6.28	9.26	23152	22500	600	0.32	2.59	6.0	
AVE	"	1.52	1.465	6.36	9.32	23311	22780	510	0.22	2.18	5.90	-0.93
1	9.88	1.8	1.725	6.64	11.45	28637	26400	2200	0.88	7.68	8.5	
2	"	1.7	1.7	6.83	11.62	29058	28100	900	0.36	3.09	8.75	
3	"	1.9	1.675	7.04	11.79	29492	27600	1900	0.76	6.1	8.75	
4	"	1.8	1.75	6.45	11.29	28228	27200	1000	0.40	3.5	9.5	
5	"	1.8	1.775	6.27	11.13	27830	27400	400	0.16	0.72	8.75	
AVE	"	1.8	1.725	6.65	11.46	28649	27340	1100	0.51	4.22	8.86	-1.02

TABLE 8:

VALIDATION OF IMPULSE SYSTEM USING CORD DRIVE AND 1.875 KG. WEIGHT ON A SEPARATE OCCASION FROM DATA COLLECTED IN TABLE 5

CHAPTER IV

APPLICATION

SPRINTING VELOCITY

Instantaneous velocity curves of the upper torso of three female and six male sprinters were obtained. Descriptive data on these sprinters has been tabulated in Table 9.

Six sprinters ran two 100 meter sprints, and three male sprinters ran one 100 meter sprint, the results of which were averaged and recorded in Table 10.

Figure 13 represents the graph of the fastest velocity recorded. (A sample recording from one female and one male sprinter has been included in Appendix 3.).

As expected, the fastest velocity was recorded by the sprinter with the best previous 100 meter time (10.6 seconds). It was interesting that the time for this sprint was not the faster of the two trials for this subject (12.1 seconds compared with 11.95 seconds for the other trial). Further examination of both graphs was necessary to determine that the faster sprint time had regions of relatively smooth velocity (2.5 meters at 9.52 meters per second) and the sprint velocity pattern was not as uneven throughout the sprint. The subject also managed to finish the 11.95 second sprint at

9.04 meters per second whereas his velocity had dropped to 8.4 meters per second in the 12.1 second sprint. In the 11.95 second sprint the subject reached top speed much earlier, at 21 meters instead of at 60.5 meters as in the 12.1 second sprint.

Female sprinter number 2 encountered a strong headwind during her second sprint and the effect on her sprinting velocity and pattern can easily be seen in Figure 14. The headwind occurred at approximately 38 meters into the sprint, as recorded on the Honeywell XYY' recorder and as reported by the subject. The subject's first sprint has been included in Figure 14 for comparison of the second sprint with her normal pattern of sprinting.

The two sprints of subject number 7 were run in virtually the same time (12.45 seconds and 12.425 seconds) and yet the sprinting patterns were very different. The fastest sprint had a faster start, higher top speed (9.44 meters per second compared with 8.88 meters per second) and higher velocity at the 100 meter mark (8.28 meters per second compared with 7.88 meters per second); however, it took longer to reach top speed (at 53 meters versus 33 meters), the top velocity was not held as long (0.5 meters versus 1.0 meters), the pattern of sprinting was much more erratic, and the subjective feeling of effort was much greater.

It has been the writer's opinion for some time that sprinting at less than top speed would produce more consistent results and produce the same

or better times as "all-out" efforts. Gradually increasing the top speed of the sprint, yet maintaining a consistent, even run would have the potential of making large reductions in sprint times possible. It was obvious that the effect of experimentation with sprinting styles could be studied quite simply using the velocity recorder. Further than this, the sprinter had some feedback on which of two sprints was run the better and why (even though the two times may have been identical).

Generally speaking, as the quality of the sprinter improved, it could be seen that the top speed reached was higher, the top speed was reached more quickly, and the top speed was held longer. With regards to any particular sprinter, the better sprints were not necessarily the ones with the fastest velocity but more importantly the more evenly run. The results of any training program to increase speed - whether it was flexibility, treadmill, or weight training - could be evaluated effectively.

Number	Age	Height	Weight	Event (Meters)	Best Time for event (seconds)	Best 100M Time (seconds)
Females						
#2	25	5'10"	130 lb	400M	54.9	12.6
#5	19	5'4"	116 lb	400M	59.6	13.7
#3	25	5'5"	123 lb	none	-	-
Males						
#1	26	5'11"	142 lb	800M+	2:01.5	12.0
#4	25	5'8"	150 lb	none	-	-
#7	22	5'6½"	138 lb	400M	51.5	11.2
#8	19	5'11½"	135 lb	400M	51.7	12.0
#6	20	5'10"	140 lb	200M 400M	22.8 51.0	11.0
#9	19	5'9"	135 lb	200M 400M	22.4 50.2 (in doors)	10.6

TABLE 9:

DESCRIPTIVE DATA OF SPRINTERS

	Trial	Time (seconds)	Top Speed (M/sec.)	At (meters)	Top Speed Held for (Meters)	Speed at 100M (M/sec.)
Females #2	1	14.15	7.56	34	2.5	6.72
	2	14.3	7.8	39	0.5	6.24
#5	1	14.2	7.64	63	0.5	7.20
	2	13.95	7.44	24.5	0.5	6.24
#3	1	17.3	6.54	16	0.5	5.04
	2	17.7	6.84	26	0.5	5.36
Males #9	1	12.1	9.92	60.5	0.5	8.4
	2	11.95	9.52	21	2.5	9.04
#7	1	12.45	8.88	33	1.0	7.88
	2	12.425	9.44	53	0.5	8.28
#1	1	13.35	8.40	58	1.0	6.68
	2	13.5	8.20	41	1.0	7.36
#8	1	12.98	8.98	46	0.5	7.96
#6	1	13.1	8.88	37	1.5	7.92
#4	1	13.53	7.76	26	0.5	6.96

TABLE 10:
COMPARATIVE DATA OF SPRINTERS
FOR 100 METER SPRINTS

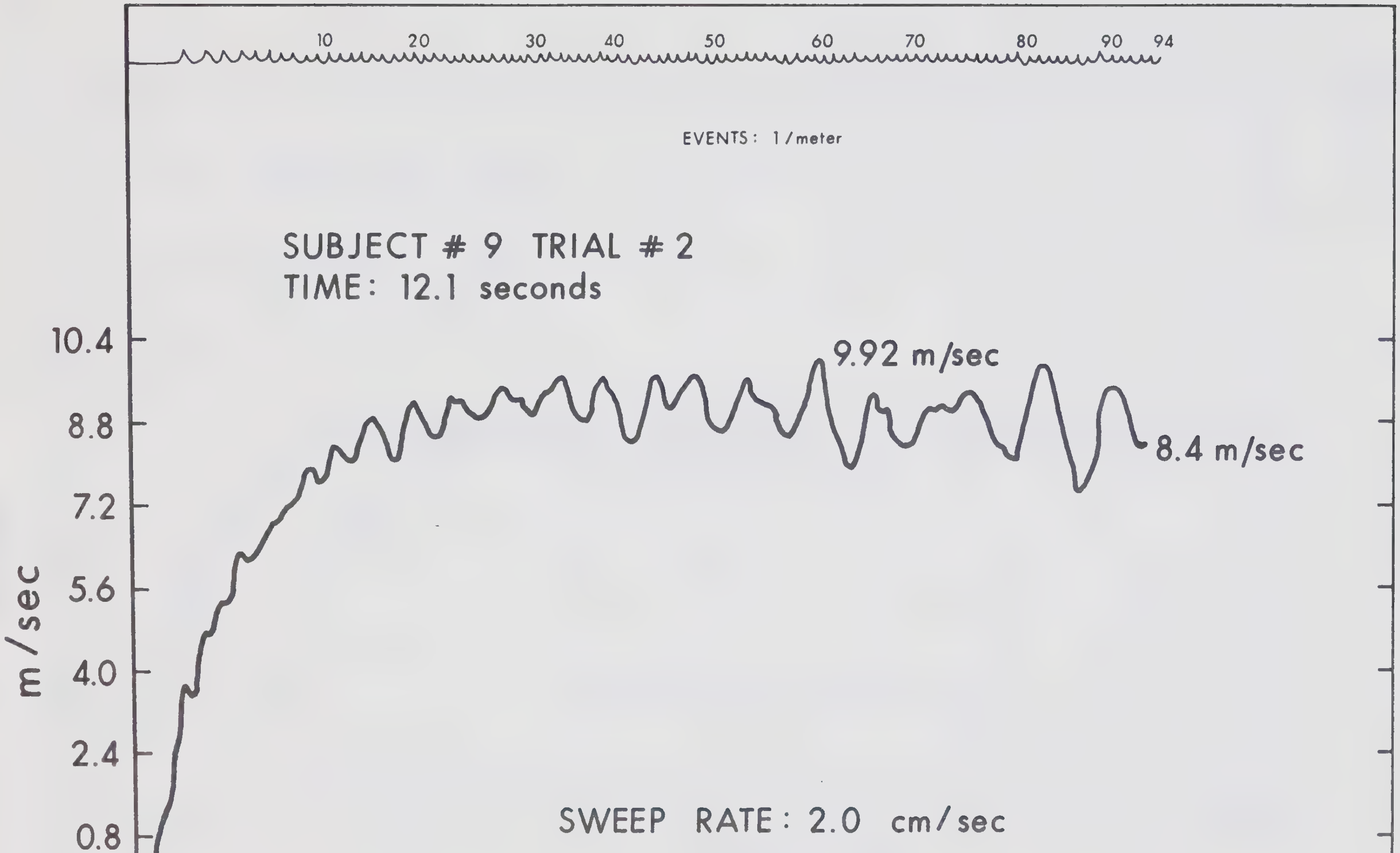


FIGURE 13:

GRAPH OF FASTEST SPRINT VELOCITY RECORDED

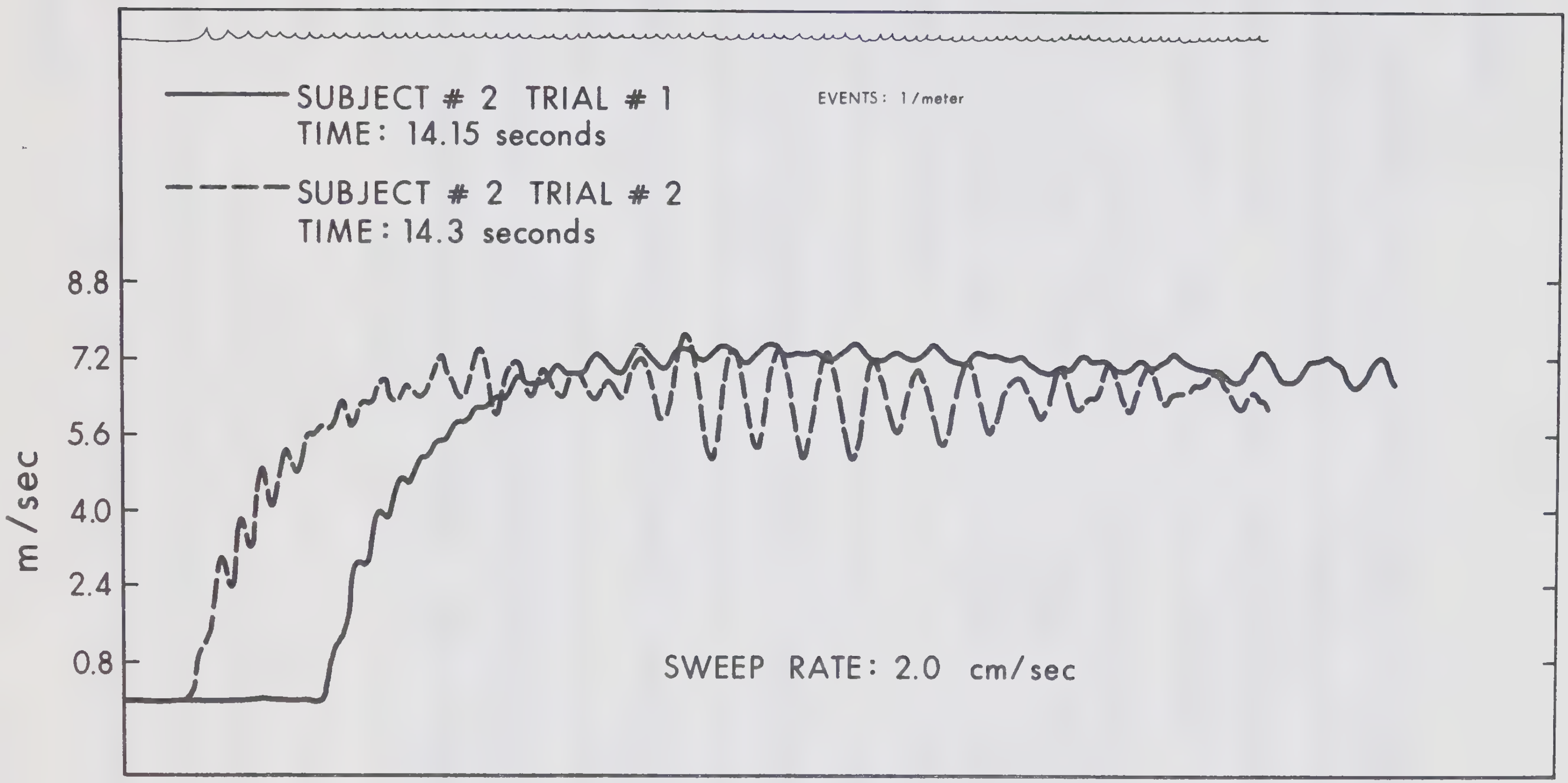


FIGURE 14:

THE EFFECT OF A STRONG HEADWIND (TRIAL #2) ON SPRINTING VELOCITY

ACCURACY

Although the validity and reliability of the velocity recorder had been established there still remained several questions concerning its accuracy with sprinters. For example, it was thought that due to stretch or sag there may be more than 100 meters of cord out at the 100 meter mark of the sprint. As previously mentioned, the amount of stretch in the cord was very small (0.8% per 0.454 kg. of load). Through measurement it was found that the cord would sag 0.305 meters in 20 meters. The velocity recorder was mounted (See Plate 3) 1.12 meters off the ground; therefore, the cord did not touch the ground until the 75 meter mark. Since the amount of sag was small in comparison to the distance over which it sagged, it was expected that little extra cord would be pulled out as a result of the sag (theoretically, 0.045 meters). This was found to be true when the actual amount of cord out at 100 meters was measured; there was an excess of 0.127 meters of cord. The above measurements were made under conditions of no wind. The sprinter is the dominating force pulling out cord and it was observed, but not measured, that during the sprint no extra cord is pulled out by the wind. However, as soon as the sprinter slowed after completing the sprint, a cross wind was able to pull out several extra meters of cord. Since it was not possible to measure whether in fact extra cord was pulled out by a cross wind during a sprint, validity under these conditions can not be assumed.

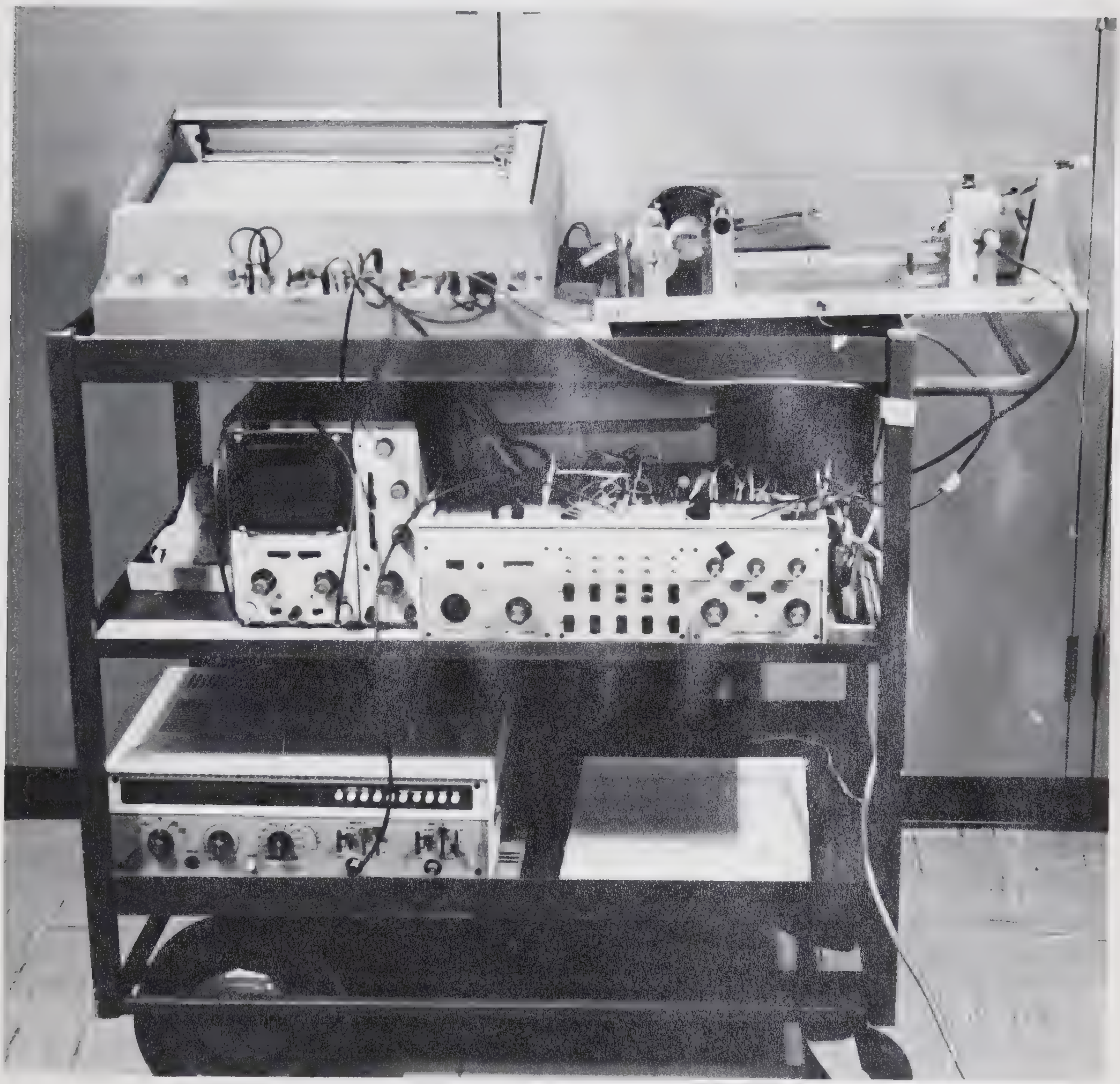


PLATE 3:

VELOCITY RECORDER AND EQUIPMENT

Top Shelf: (l to r) Honeywell XYY' Recorder, Instantaneous Velocity Recorder

Middle Shelf: (l to r) Oscilloscope, Heath Analog Digital Designer

Bottom Shelf: Heath Digital Frequency Meter

It had been determined previously that there was approximately 3% error in the velocity recording and in the event marker over distances up to 10 meters. Over 100 meters the error in the event marker was approximately 4%. (See Table 11)

There were several equally valid possibilities which might explain this small amount of error. It could be partly due to slippage of the cord over the drive wheel, or partly due to the degree of precision in machining the drive wheel to the correct diameter. (See section entitled "Validity" in Chapter III for a complete discussion of possibilities to account for this error.)

OTHER USES

The velocity recorder could be used to measure the velocity of any object or person which moves over a straight distance and slower than twelve meters per second. For example, skiiers, skaters, cyclists or rowing crews could be studied. Most likely, some provision for measuring velocity around a curve could be devised as well. The major problem to overcome would be to keep the cord moving in the same arc as the subject; but most likely a series of smooth poles could be set out to accomplish this.

The velocity recorder also would have potential as a convenient teaching device providing immediate feedback to the subject. For example, rowing crews often win or lose a race on the basis of their start. Many styles of starting could be studied and evaluated for their potential.

Subject	Trial	Distance	# of Event Markers	% Error
3	1	100 Meters	97	3.0
	2	"	95	5.0
5	1	"	95	5.0
	2	"	95	5.0
2	1	"	95	5.0
	2	"	97	3.0
9	1	"	94	6.0
	2	"	94	6.0
7	1	"	95	5.0
	2	"	97	3.0
1	1	"	96	4.0
	2	"	95	5.0
8	1	"	98	2.0
6	1	"	97	3.0
4	1	"	95	5.0
AVERAGE:			95.67	4.33

TABLE 11:

EVENT MARKER ERROR

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

A measuring system was developed for obtaining instantaneous sprinting velocity curves over the distance of 100 meters. Instantaneous velocity in this context referred to average speed over a short distance (8 to 80 centimeters). (See Figure 7) The velocity recorder was tested over the speeds of zero to twelve meters per second. Evaluation of the measuring system proved it to be an accurate (97%) and reliable (95%) means of recording sprinting velocity. It was postulated that the small amount of error in its accuracy might be due to any of several possibilities including: cord slippage over the drive wheel, precision in machining the drive wheel, or delay time due to averaging. (See Chapter III).

Although the device was designed for use with sprinters, it was suggested that it could readily be used with any object or person which travels in a straight line and at speeds of less than twelve meters per second.

The following major improvements, if made, would extend the capabilities of the velocity recorder, contribute to its portability and enhance its ease of operation.

The Honeywell XYY' recorder could be replaced by a Honeywell Visicorder Model 4408A001 and Honeywell Accudata 107DC Amplifier. At present, average speed was limited to a time constant which matched the pen response of the XYY' recorder. The velocity recorder was built with a

capability of obtaining average speed every 1.0-10 mm. (instead of the present 8-80 cm). Thus the Honeywell Visicorder with a pen response of 25 kilohertz would easily handle the information from the velocity recorder and could give up to an eighty-fold increase in resolution of velocity. Approximate cost of this change would be $1800.

The Heath Analog Digital Designer could be replaced by a "hand wired" package of components and Heath Digital Power Module. The circuitry would remain identical but the size of the unit could be drastically reduced and thus could be mounted on the aluminum base plate of the velocity recorder. Approximate cost of this reduction in size (including components) would be $250.

The incandescent bulb of the velocity recorder could be replaced by a compact (2 inch diameter x 14 inches long) helium-neon laser. The laser should be single mode ($T.E.M._{00}$) to allow for focusing of the beam. A one milliwatt laser complete with power supply would be commercially available from Metrologic or Spectra-Physics for approximately $200. Since a laser could be focused and the intensity adjusted to saturate the photodiode with light at every slot, a large increase in operating velocities could be recorded. Some gains would also be possible in the size of the chopper needed since the width of the slots could be reduced. The laser would also offer the convenience of a greatly increased operating lifetime.

Minor changes could be made in the velocity recorder to reduce the overall size but since the recorder's present size would be compact enough for most applications, no reductions in size are recommended.

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APPENDIX 1.

SAMPLE RECORDINGS

OBTAINED DURING CALIBRATION

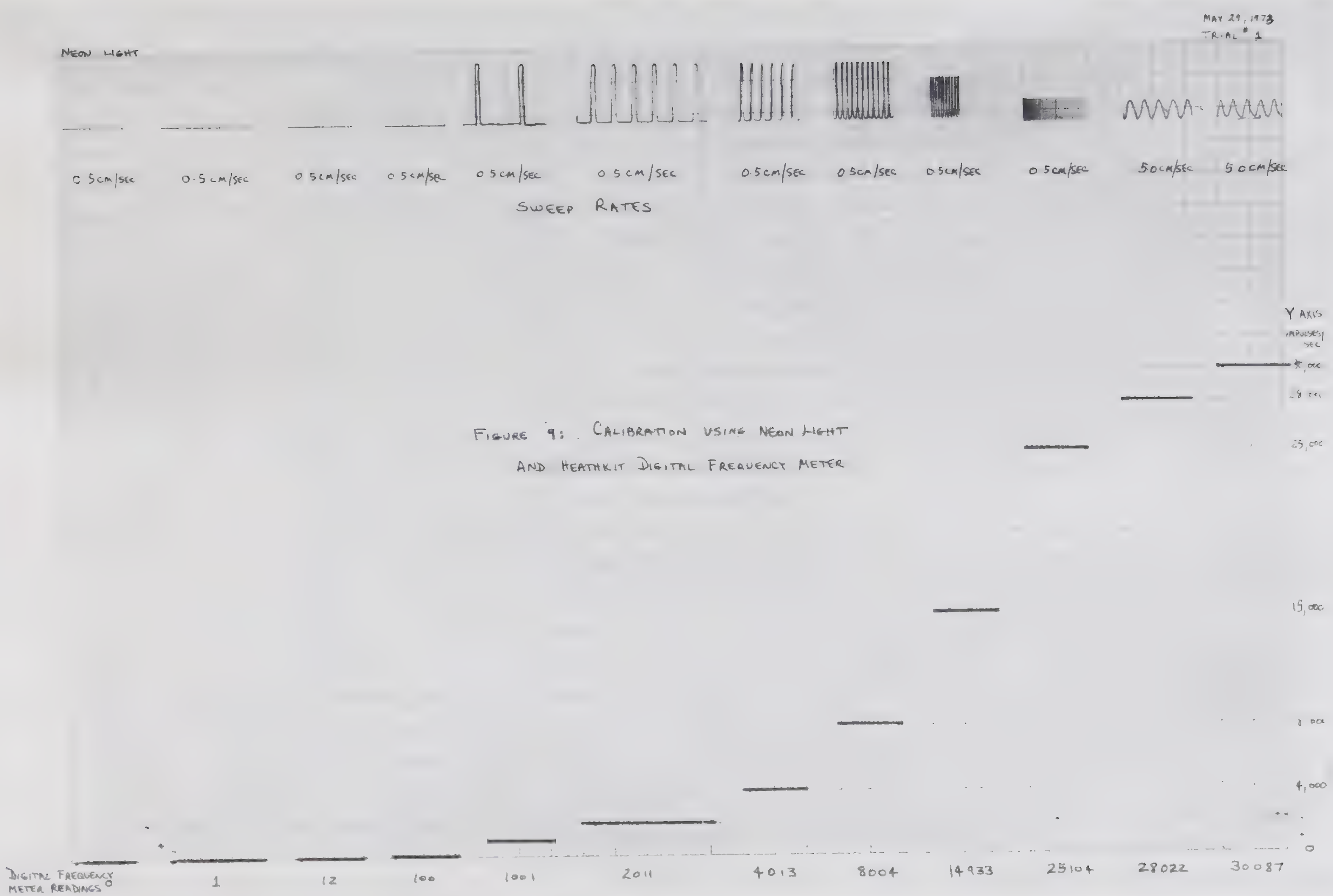


PLATE 4: CALIBRATION USING NEON LIGHT AND HEATH DIGITAL FREQUENCY METER

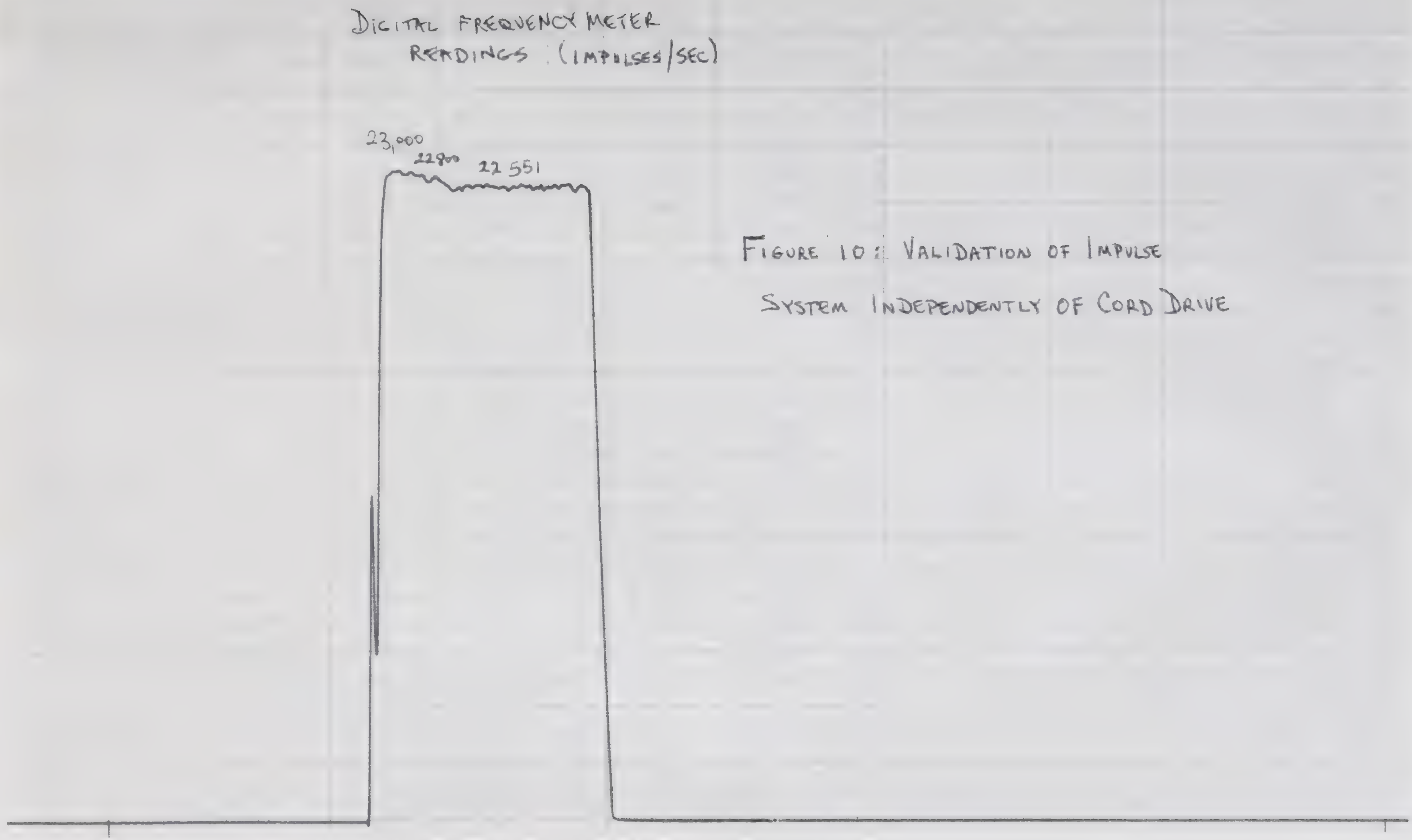


FIGURE 10: VALIDATION OF IMPULSE SYSTEM INDEPENDENTLY OF CORD DRIVE

PLATE 5 : VALIDATION OF IMPULSE SYSTEM INDEPENDENTLY OF CORD DRIVE

APPENDIX 2.

SAMPLE RECORDINGS

OBTAINED AT SIX DIFFERENT HEIGHTS

WITH TWO DIFFERENT WEIGHTS

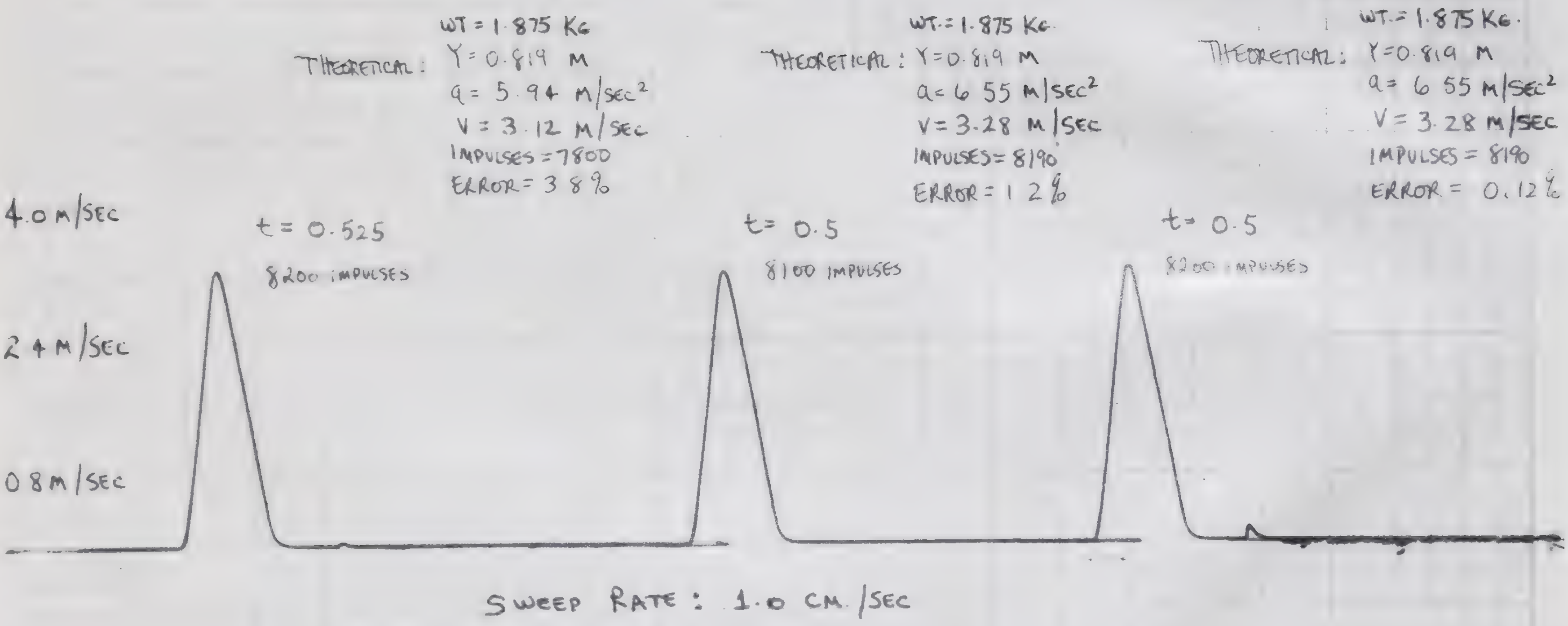


PLATE 6: VALIDATION OF RECORDER USING A 1.875 KG. WEIGHT FROM A HEIGHT OF 0.819 METERS

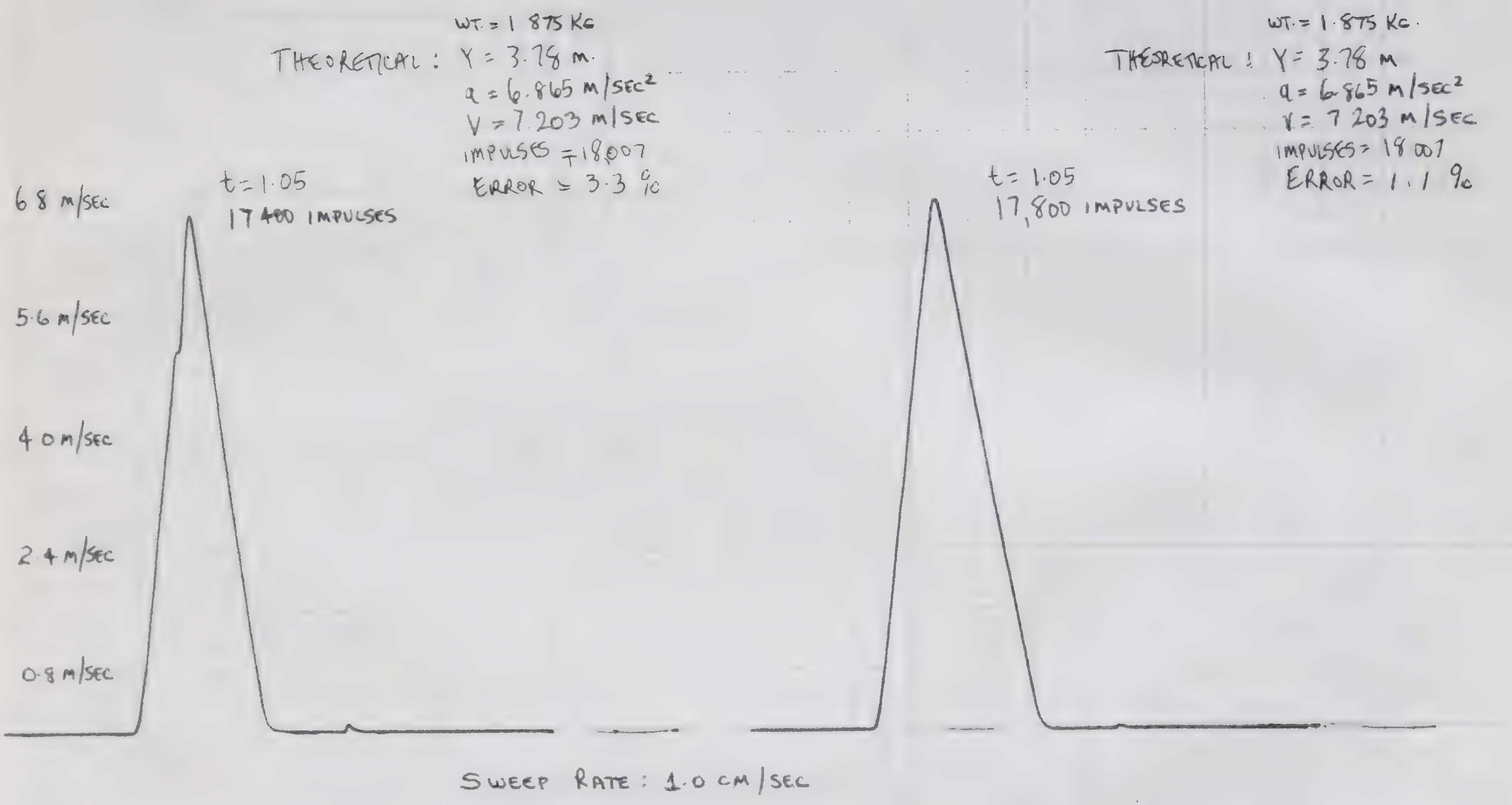
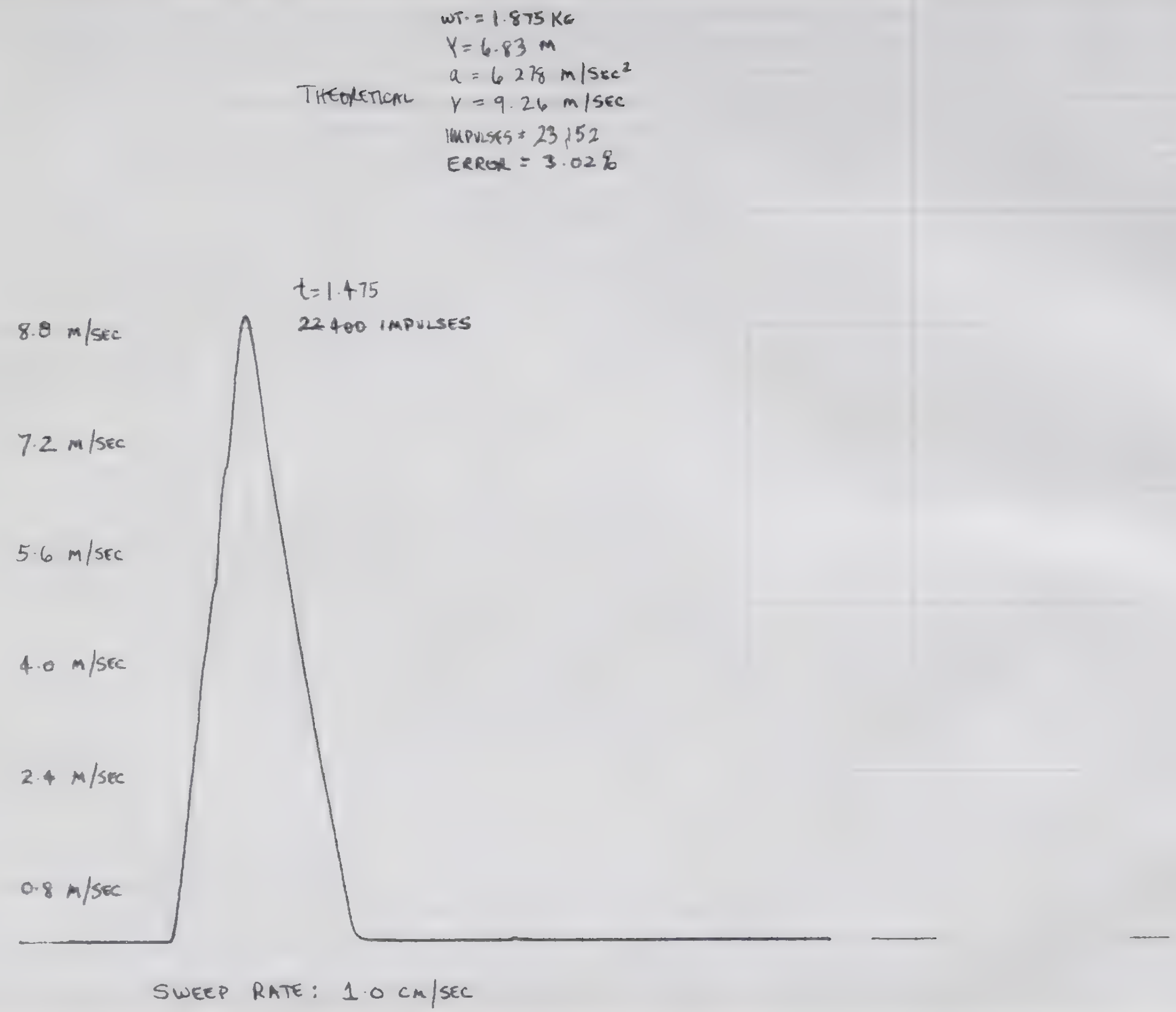


PLATE 7: VALIDATION OF RECORDER USING A 1.875 KG. WEIGHT FROM A HEIGHT OF 3.78 METERS



LATE 8: VALIDATION OF RECORDER USING A 1.875 KG. WEIGHT FROM A HEIGHT OF 6.83 METERS

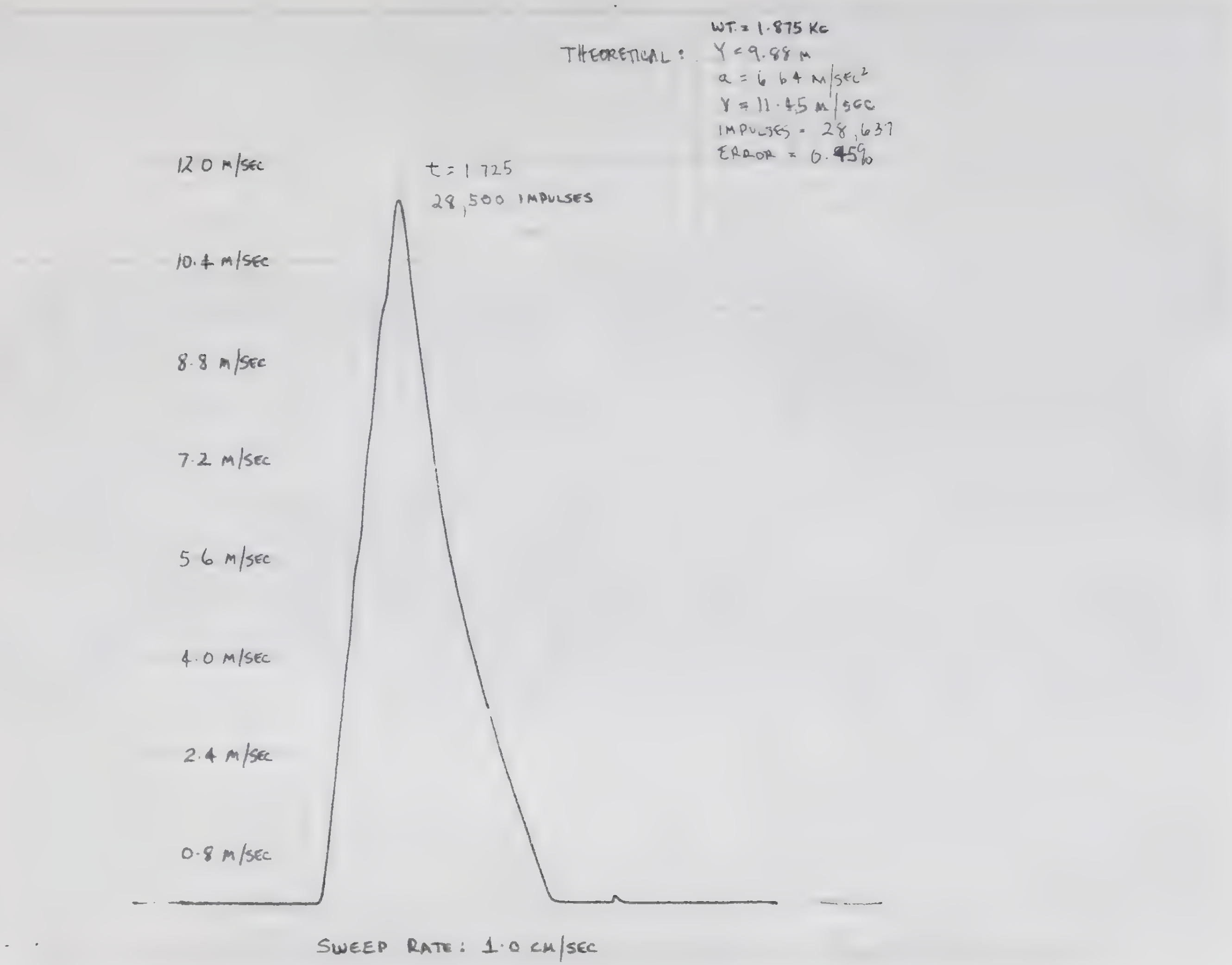


PLATE 9: VALIDATION OF RECORDER USING A 1.875 KG. WEIGHT FROM A HEIGHT OF 9.88 METERS

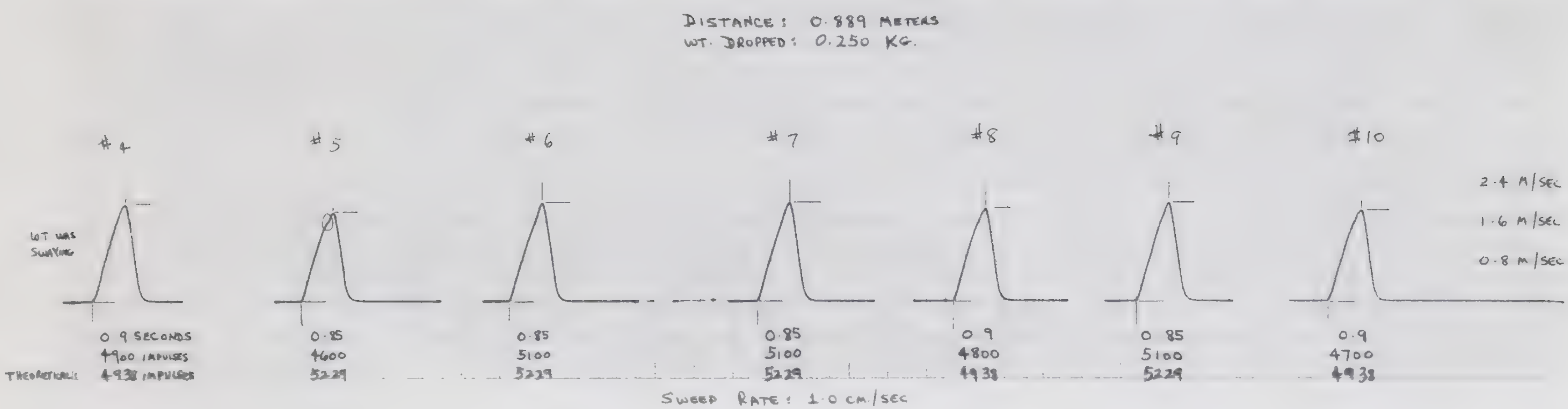


PLATE 10: VALIDATION OF RECORDER USING A 0.250 KG. WEIGHT FROM A HEIGHT OF 0.889 METERS

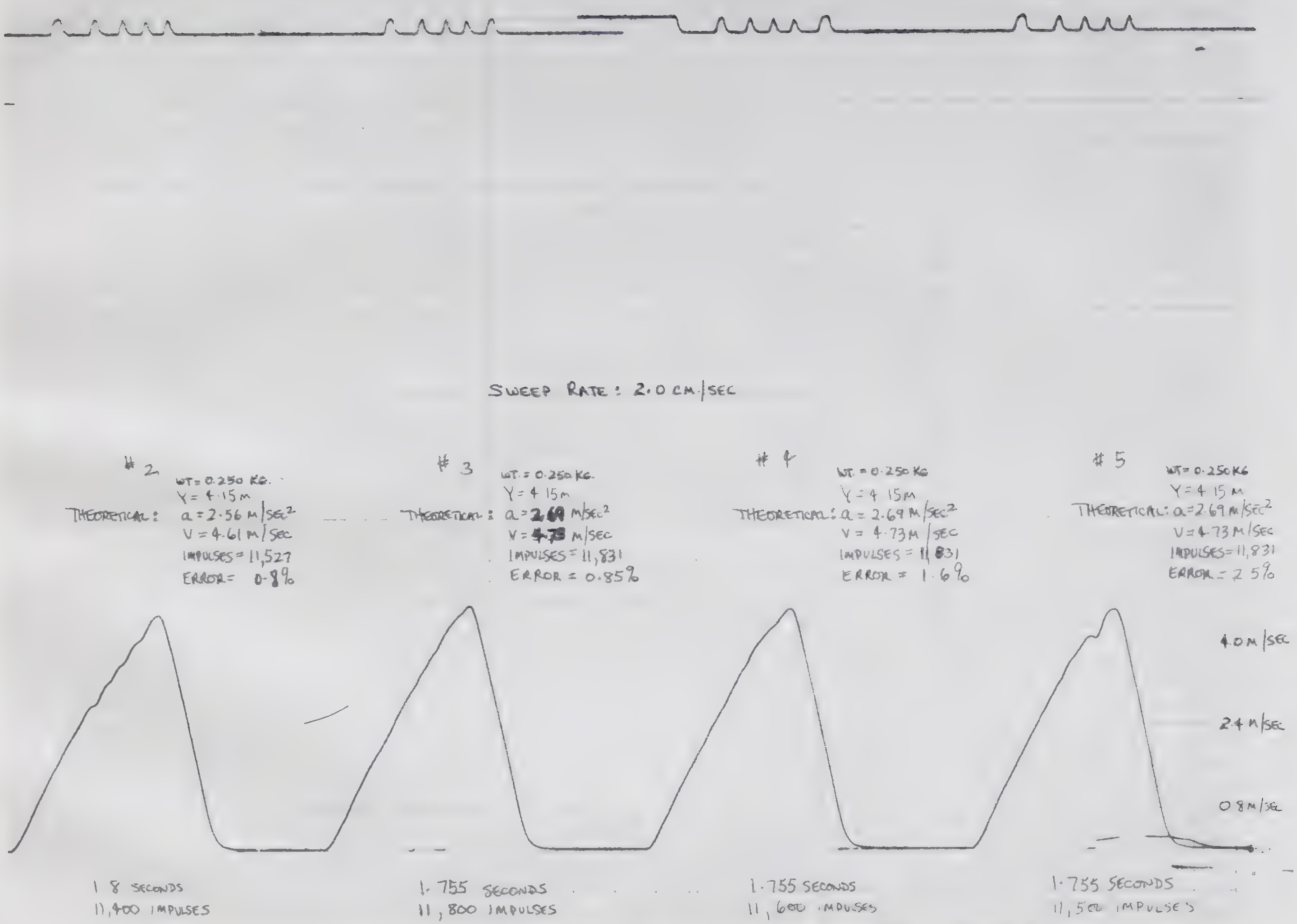


PLATE 11 : VALIDATION OF RECORDER USING A 0.250 KG. WEIGHT FROM A HEIGHT OF 4.15 METERS

APPENDIX 3.

SAMPLE RECORDINGS

OF 100 METER SPRINTS

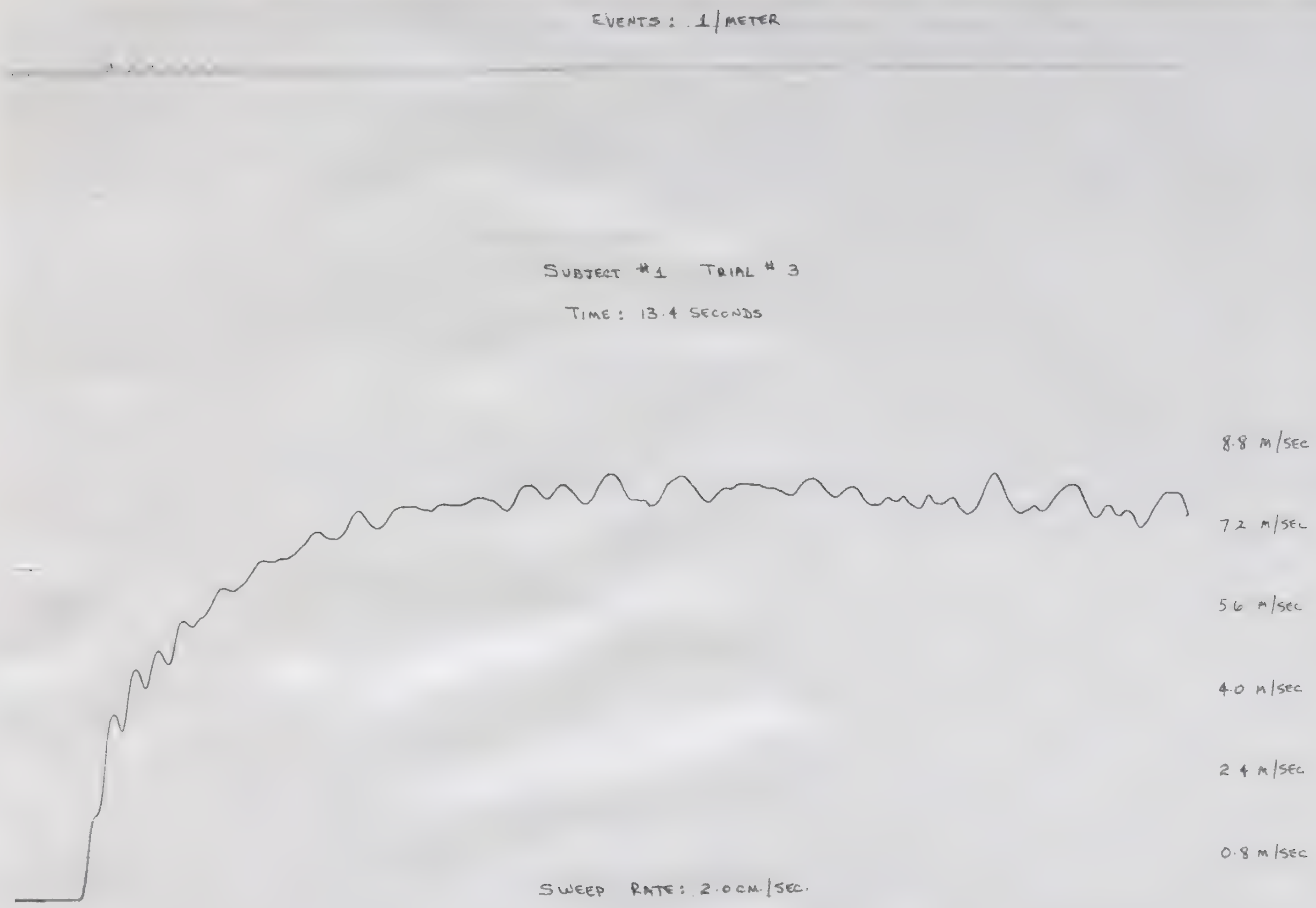


PLATE 12 : SAMPLE RECORDING OF A MALE SPRINTER
(PERSONAL BEST FOR 100 METERS - 12.0 SECONDS)

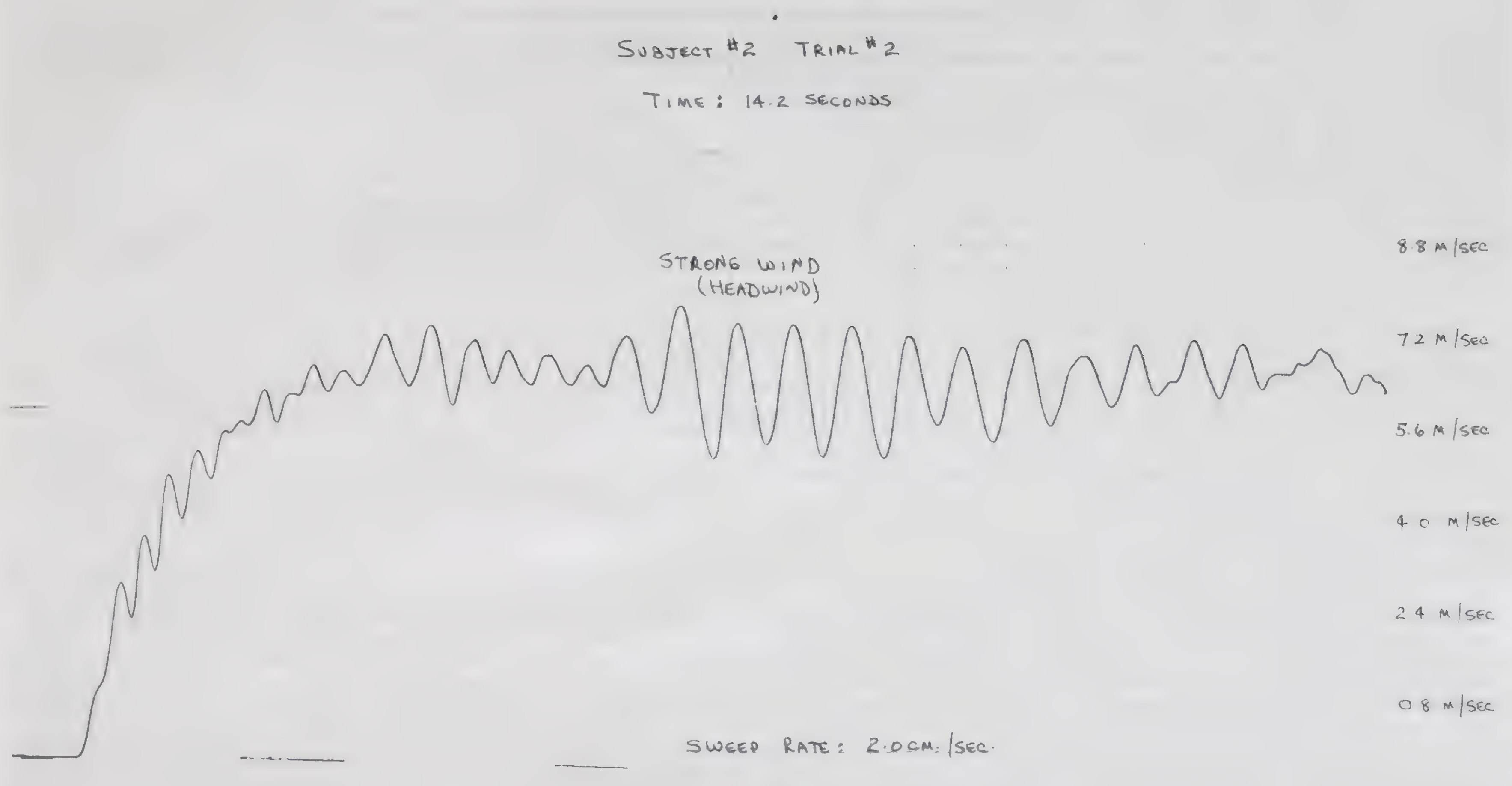


PLATE 13: SAMPLE RECORDING OF A FEMALE SPRINTER ENCOUNTERING A STRONG HEADWIND AT 38 METERS (PERSONAL BEST FOR 400 METERS — 54.9 SECONDS)